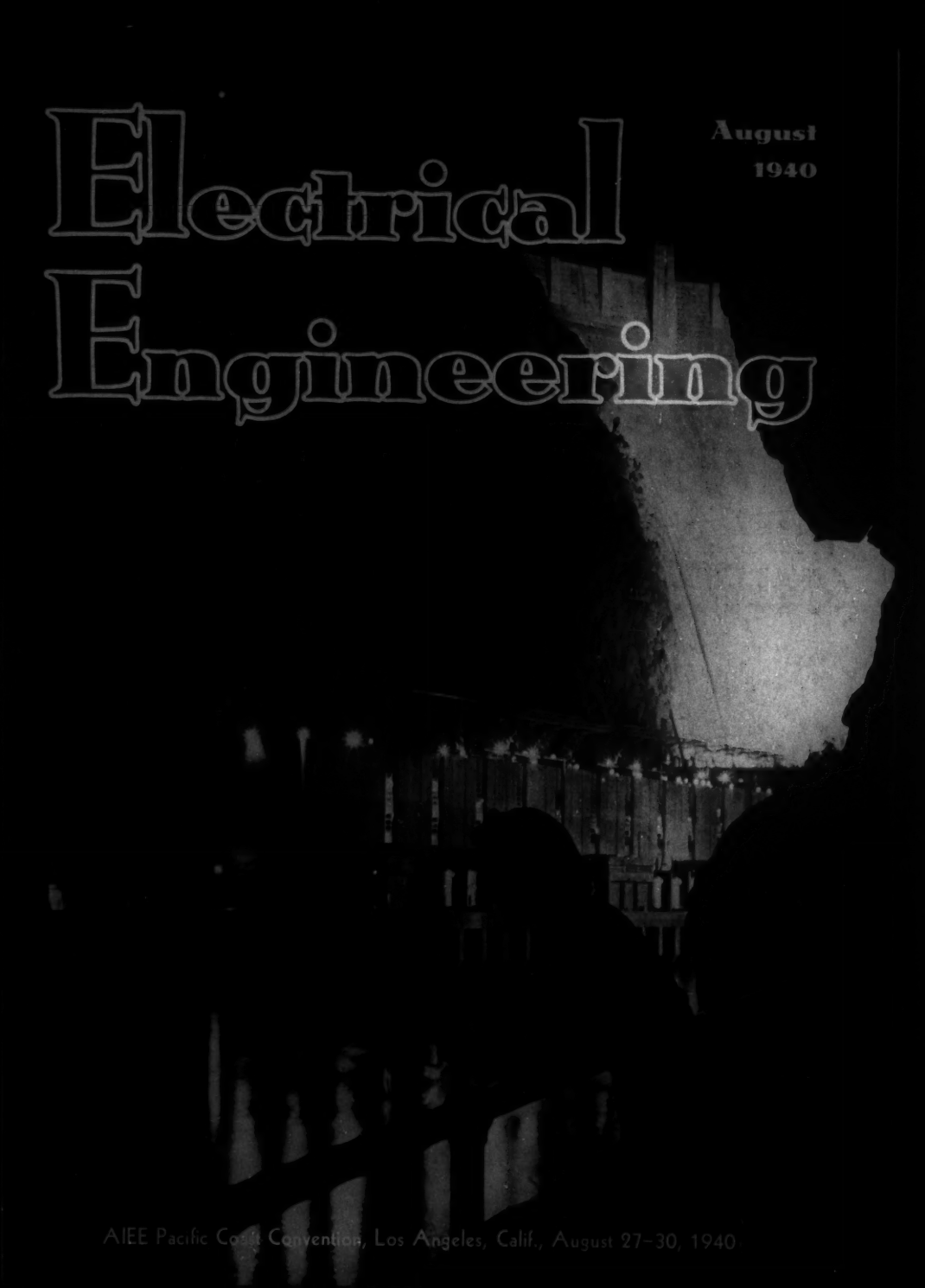
# Electrical Engineering

August
1940



AIEE Pacific Coast Convention, Los Angeles, Calif., August 27–30, 1940

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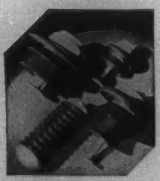

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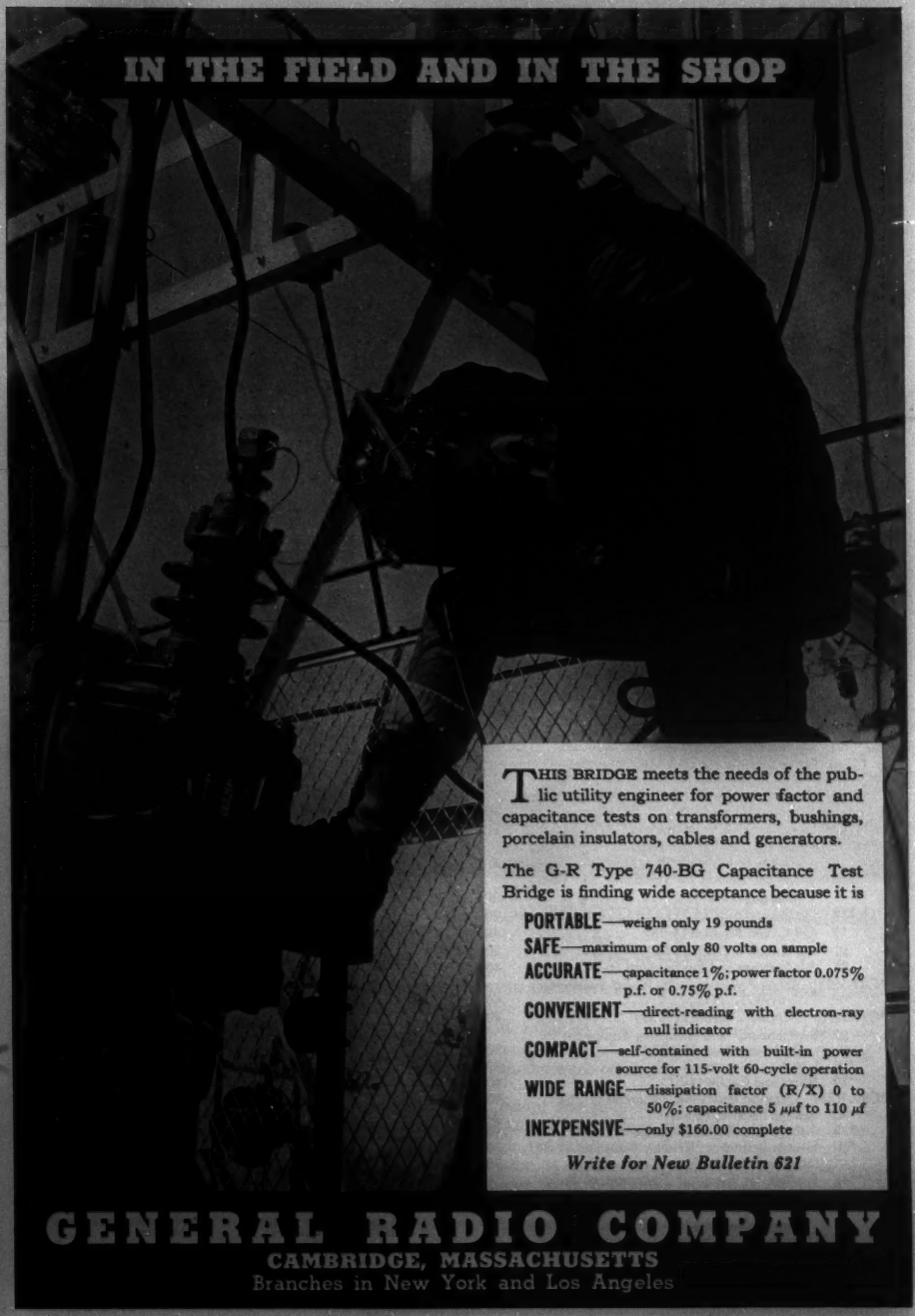


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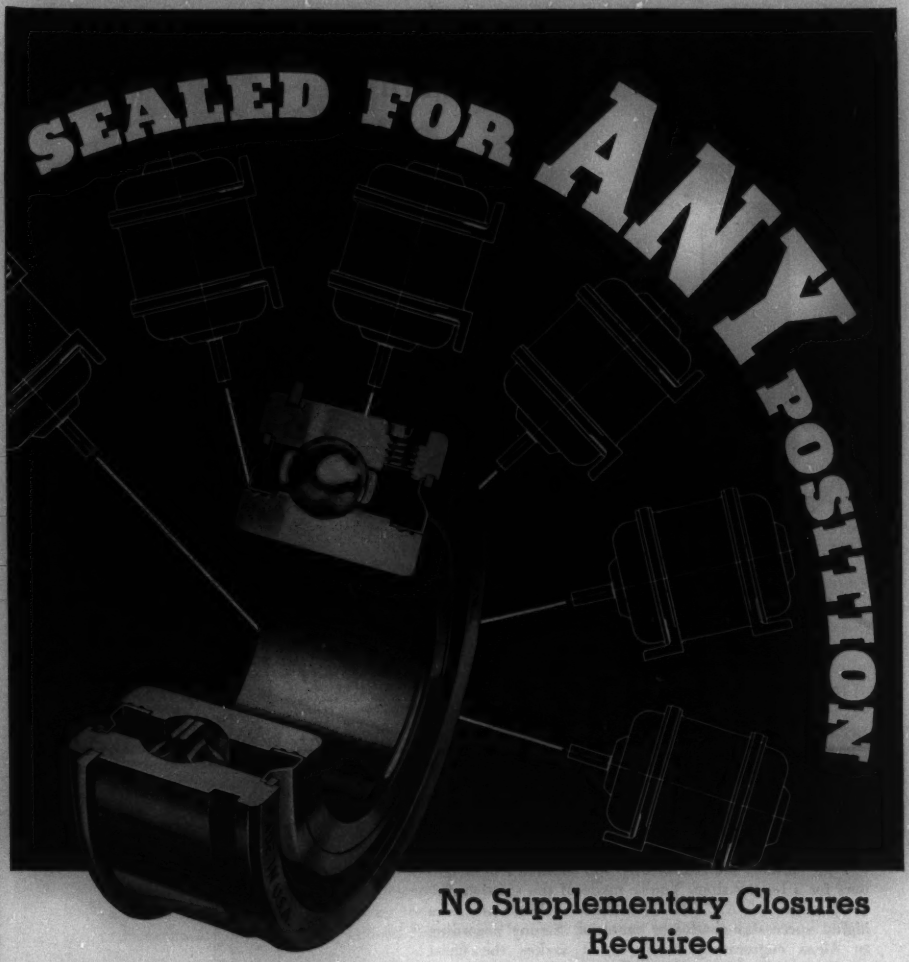


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# Electrical Engineering

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## for August 1940—

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¶ Correspondence is invited on all controversial matters.

# High Lights • •

**Publication Policy.** To improve the Institute's publication service to its members within prevailing budget limits, a series of proposals recommended by the publication committee, and endorsed by the conference of officers, delegates, and members at Swampscott, were approved by the board of directors at its summer-convention meeting. Certain of these proposals are effective with this issue of ELECTRICAL ENGINEERING; others will be placed in effect as rapidly as possible. Principal among the ultimate results to be achieved are the inclusion of more technical papers in ELECTRICAL ENGINEERING, and a very substantial reduction in the delay that has prevailed between presentation and publication of a technical program paper. Great credit is due to Chairman I. Melville Stein of the publication committee and to those who have worked with him (*pages 331–2*).

**Watt-Hour Meters.** The characteristics of watt-hour meters are dependent upon many diverse factors interrelated in a complex way. A type of load that may affect the registration of watt-hour meters is the mercury-arc power rectifier, which introduces harmonics in the current and voltage waves. Tests on 6- and 12-phase rectifiers indicate that the registration will be affected by less than one per cent (*Transactions pages 449–57*). On certain intermittent loads meters may have registration errors, the magnitudes of which are functions of meter design, periodicity of intermittent component of load, ratio of intermittent component to total load, character of intermittent component, power factor of load, and adjustment of the friction compensation. Prediction of registration characteristics may be made from acceleration and deceleration curves for the meter disk (*Transactions pages 460–4*).

**Television.** Although predictions that commercial television is "just around the corner", often heard during recent years, have failed to materialize, 3 stations now are broadcasting television programs on a regularly scheduled basis; 19 others have been licensed by the Federal Communications Commission, and applications for licenses for some 20 other transmitters have been filed with the Commission. In this issue, an authority on the subject reviews briefly the history, principles of operation, and present status of this new means of communication (*pages 313–22*).

**Summer Convention.** In addition to the general résumé of activities at the recent summer convention (*pages 333–5*), this issue includes a digest of the discussion at the annual conference of officers, delegates, and members (*pages 335–7*), a summary of the convention meeting of the board of directors (*page 340*), and reflections of the salient points discussed at the several informal technical conferences (*pages 337–40*).

**Lightning.** A co-operative field investigation of the lightning currents discharged by arresters at stations was undertaken in 1936; data so far obtained show large variations in the duty on arresters because of local conditions and seasonal changes (*Transactions pages 417–22*). An investigation of the effect of lightning on distribution systems indicates that arrester discharge currents of low magnitude and long duration may occur, and that such discharges are more likely to cause arrester failure than very high currents of short duration (*Transactions pages 442–9*).

**Inductive Interference.** Telegraph lines may have extraneous currents induced in them by power-supply and distribution systems that reduce the capacity and dependability of the lines. One method of control is the application of mitigative equipment to the telegraph system by which either a voltage to neutralize the interference is applied to the telegraph wires, or a combination of reactors and capacitors reduces extraneous sinusoidal currents by tuning (*Transactions pages 469–74*).

**Motor Characteristics.** The ability to obtain accurate characteristics of induction motors without actually measuring them is most desirable. In addition to the customary locked-rotor and no-load tests, two additional tests, a reverse-rotation test and an ordinary load run, provide data for calculating the characteristics (*Transactions pages 464–8*). Air-borne noise arising from an electric motor has as its principal source the vibration caused by the interaction of two large harmonic flux waves of slightly different space order and traveling at high frequency with respect to each other which cause high-frequency magnetic-force waves of long pitch (*Transactions pages 474–80*). ¶

**Transient Analysis.** The method of symmetrical components may be used for the study of transients in symmetrical networks. The method is claimed to be readily applicable to all linear dynamical systems exhibiting this type of symmetry whether electrical or mechanical (*Transactions pages 457–9*).

**Lamme Medal.** Medal presentations frequently provide opportunity for interesting and stimulating backstage views of careers and personalities. The occasion of the presentation to Norman W. Storer of the Institute's 12th Lamme Medal during the summer convention at Swampscott, Mass., was no exception (*pages 322–5*).

**Spark Gaps.** A hitherto unrecognized factor responsible for the low impulse breakdown voltage of short enclosed spark gaps such as are used in lightning arresters has been found to be radiation from the region of the contact junctions between insulator and metal electrode (*Transactions pages 429–33*).

**Water in Dielectric Liquids.** Cellulosic insulation for high voltages must be maintained in a dry condition for successful operation. However, it may be brought to a hazardous condition in service by water absorption from the surrounding atmosphere through the insulating liquid (*Transactions pages 433–41*).

**Electric Couplings.** Electromagnetic forces may be used for transmitting torque, and couplings in marine service using these forces serve a threefold purpose by acting as a flexible coupling, as a disconnecting clutch, and as an aid in maneuvering (*Transactions pages 423–8*).

**Current Transformers.** Large errors of transformation may be expected of standard current transformers during the starting period when the current wave may be fully offset; actual performance must be determined if a suitable high-speed relay scheme is to be chosen (*Transactions pages 481–8*).

**Pacific Coast Convention.** The complete technical program and other details of the forthcoming Pacific Coast convention at Los Angeles, Calif., are included in this issue (*pages 332–3*).

**Coming Soon.** Among special articles and technical papers currently in preparation for early publication are: Two articles on the topic of transportation as a social problem as discussed at the recent summer convention in Swampscott, Mass., by Colonel William J. Wilgus in behalf of immediate government ownership and operation of American railroads, and by Colonel Robert F. Henry ardently in support of continued private enterprise; an article embracing the substance of the summer convention banquet address by L. A. Hawkins (A'03, M'13) vigorously urging engineers and scientists to bend and blend every possible effort toward the creation of the modern war materials and equipment necessary for adequate national defense; a paper describing a proposed method for the determination of current-transformer errors by G. Camilli (M'27) and R. L. Ten Broeck (A'29); papers on bushing-type current transformers by C. A. Woods, Jr. (A'37) and S. A. Bottonari (A'37), and J. P. Gebelein and J. A. Elzi (M'38); a paper discussing what wood may add to primary insulation for withstanding lightning by Joseph T. Lusignan, Jr. (M'34) and Charles J. Miller (A'32); papers on air circuit breakers by W. S. Edsall (M'19) and S. R. Stubbs; L. R. Ludwig (A'28) and R. H. Nau (A'40); L. R. Ludwig (A'28), H. L. Rawlins (A'30), and B. P. Baker (A'38); D. C. Prince (F'26), J. A. Henley, and W. K. Rankin; and H. E. Strang (M'40) and A. C. Boisseau; a paper on network coupling by means of static electronic frequency changers by Othmar K. Marti (F'39); papers on railway power supply by E. R. Hill (F'12) and Philip Torchio (F'12); and a paper on electric braking for railroad and urban transit equipment by F. H. Craton (M'38) and F. M. Turner

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# TELEVISION

GEORGE R. TOWN
MEMBER AIEE

**Television on a commercial basis similar to that of present-day radio-broadcasting has been predicted for some years, but experimental work has been costly and the technical problems involved in developing a satisfactory system have been extremely difficult. More recently, the problem of standardizing on a generally acceptable system has become an obstacle. The result has been that commercial television as commonly envisioned has been somewhat delayed. However, television broadcasts on a regularly scheduled basis began April 30, 1939, in connection with the opening ceremonies of the New York World's Fair, and now regular television programs are broadcast from 3 stations in the United States. Furthermore, 19 additional stations in 12 cities have been licensed by the Federal Communications Commission, and applications are pending for some 25 other transmitters in 18 cities. This activity, together with the increasing public interest in television, would seem to indicate that commercial television, at least in the urban centers, is not far off. The history of this new means of communication, its principles of operation, and its present status are reviewed briefly in this article.**

TELEVISION is defined as the electrical transmission and reception of transient visual images. The word "electrical" excludes from the domain of television any completely optical device for viewing distant objects—for example, the telescope. The word "transient" implies that complete pictures are transmitted rapidly and excludes facsimile transmission where several minutes are required to send a single picture. In television, a complete picture is transmitted within the period of retentivity of the eye.

The history of television falls into three periods: fundamental discovery and invention, development, and realization.

## PERIOD OF FUNDAMENTAL DISCOVERY AND INVENTION

Five fundamental devices are involved in successful television systems. The first of these depends upon the interaction of light and electricity. The variation in the resistance of a piece of selenium with incident illumination was discovered by May in 1873. This was followed by the discovery of the photoelectric effect by Hertz in 1887. Photoelectric cells, the basis of all television picture generators, were developed by Elster and Geitel between 1889 and 1913.

As early as 1879, Cary recognized that practical picture transmission can be accomplished only if the picture is divided into a number of small elements and the light values on each transmitted in rapid succession. This principle, known as scanning, was developed further by Nipkow, beginning in 1884. Although the Nipkow scanning disk is no longer used, scanning is as much a necessity in television today as in 1880.

The third important element needed in television transmission and reception is the vacuum tube. Important milestones in the development of this device were the discovery of the Edison effect in 1883, the invention of the two-element valve by Fleming in 1904, the introduction of the grid by DeForest in 1907, and the many important inventions of Armstrong. A specialized type of vacuum tube is the cathode-ray tube. Cathode rays were discovered by Pflucker in 1859, and the first practical cathode-ray tube was developed by Braun in 1897. The application of such tubes to picture reproduction was suggested by Rosing and by Campbell-Swinton in 1907.

The amplification of television signals requires an application of the theory of electrical networks and filters. Mention should be made of the work of Heaviside, Pupin, Kennelly, Campbell, and Carson in the period between 1887 and 1919 in the development of the network theory so essential in the design of circuits for television transmitters and receivers.

The final element needed in a television system is the transmission of energy by electromagnetic waves. Although pictures may be transmitted over short distances by means of wire facilities and over longer distances by use of concentric cables, economical television broadcasting necessarily involves the use of radio waves. Hence, the work of Maxwell, Hertz, and Marconi was a prerequisite to the development of television.

## PERIOD OF DEVELOPMENT

All the fundamental elements involved in modern television were known by 1920, and it was about that date that the history of television entered its second phase—the period of development. Successful laboratory transmission of silhouettes was accomplished by Baird and by Jenkins in 1923, and in 1925 Baird transmitted half-tone pictures. The Bell Telephone Laboratories experimented with picture transmission between New York and Washington over wire lines in 1927. The year 1928 was notable in two respects. It saw the transatlantic transmission of pictures by Baird on a carrier frequency of approximately 6.7 megacycles, and the inauguration of television broadcasting by the General Electric Company's radio station WGY at Schenectady.

The development of television was greatly stimulated by the invention of two all-electronic picture pickup devices—the Farnsworth image dissector (1930) and the Zworykin Iconoscope (1933). The Bell Telephone Laboratories developed the scanning disk to a high degree of perfection and with it demonstrated high-quality picture transmission in 1937. However, the electronic pickup devices are so much more satisfactory from the standpoints of high sensitivity, high resolution, low cost, easy portability, and freedom from maintenance troubles that they have

GEORGE R. TOWN is engineer in charge, television laboratory, Stromberg-Carlson Telephone Manufacturing Company, Rochester, N. Y.

supplanted the scanning disk and other similar mechanical pickup systems.

The important part played in the development of television by the television committee of the Radio Manufacturers' Association must be mentioned. The contribution of this committee, which was organized in 1930, has been largely that of co-ordinating the work of the various television laboratories and setting standards of television transmission. The importance of television standards with respect to certain aspects of transmission cannot be overemphasized. Many methods are available for performing each of the many functions essential to a successful television system. Receivers designed to operate on certain types of transmission may be unable to receive pictures from stations operating on different principles. Hence, it is important that all television transmitters have certain features in common. In setting standards, the RMA television committee consistently refused to sanction systems that were capable of producing only low-definition pictures. Their guiding policy was that it would be much better to keep television in the laboratory until systems were developed which would produce pictures that would be satisfactory to the public. The RMA television standards were adopted by the association in the fall of 1938 after extensive laboratory and field tests.

The development of television in England followed a somewhat different course. The British Broadcasting Company began experimental television broadcasts in 1929. In 1935, a television transmitter was installed for the transmission of two types of television signals. Alternate broadcasts were sent by the Baird and Marconi television systems. After several months of operation, it was decided to standardize on the latter. Television programs were broadcast regularly from 1936 until the start of the war, when all public television service was suspended. These broadcasts were subsidized by the British Government. In setting television standards in the United States, full advantage was taken of British experience. The result was that many mistakes were avoided, and it is generally agreed that American television operates on a more satisfactory technical basis than does British.

### PERIOD OF REALIZATION

With the adoption of RMA television standards in 1938, the television industry was ready to emerge into the period of realization. The situation at that time was aptly described by J. C. Wilson in his book "Television Engineering", when he stated, "The art has now reached a state in which an intelligent man might almost take an interest in it."

The year 1939 was well advertised as "the television year". Late in 1938, the National Broadcasting Company announced that it would broadcast by television the opening ceremonies of the New York World's Fair on April 30, 1939, and that thereafter it would maintain regularly scheduled television service in the New York area for public entertainment. This is quite different from experimental broadcasts at irregular intervals, and the April 30 program marked the true beginning of television service in the United States.

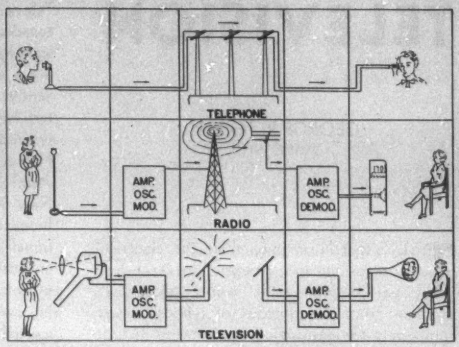



**Figure 1. Three electrical communication systems**

AMP.—Amplifier
OSC.—Oscillator
MOD.—Modulator
DEMOD.—Demodulator

Television was expected to experience a rapid growth. Manufacturers of television receivers were highly optimistic regarding public interest in television, and regarding the number of receivers that would be sold. The expectations regarding public interest have been fully realized, but in spite of this, the number of television receivers sold has been somewhat disappointing.

There are two chief reasons for the lack of greater public acceptance of television. The first of these is the price of the receivers. A high-quality television receiver, including in the same cabinet a good radio receiver, sells for approximately $600. It is quite probable that the price will be reduced in the next few years. However, the price reductions will not be on the scale that occurred with radio receivers. When radio receivers were first manufactured, they presented an entirely new production problem. The manufacturers had no previous experience with similar products. Hence, first prices were high. As production technique improved, manufacturing economies were effected, and large-scale price reductions resulted. In the television industry, the situation is quite different. Although it is considerably more complex, a television receiver has many features that greatly resemble those of a radio receiver. It uses many identical components. The same general assembly processes are used. The manufacturer of television receivers has behind him a background incomparably better than that of the pioneer radio-receiver manufacturer. Consequently, although price reductions certainly will occur, they will not be comparable with those of radio receivers.

That the public is interested in television receivers at a somewhat lower price level has been proved by a merchandising project undertaken by the Radio Corporation of America. This company offered television receivers for sale at prices approximately 34 per cent below list in Newburgh, Poughkeepsie, and Middletown, N. Y. During a three months' campaign, approximately 130 television receivers were sold. Comparing this with the fact that up to May 1, 1940, approximately 3,000 receivers had been

sold in the entire New York area, it is evident that television receivers can be sold at prices not too far below the present level, provided intensive merchandising is employed.

Polls taken in the New York area have shown that the high price of television receivers is not the most important factor delaying the widespread purchase of receivers. The most important factor is the lack of satisfactory programs. The reason that high-quality programs are not available 18 hours a day from any television station is not difficult to find. It has been estimated that the cost of providing television programs 12 hours a week is between $500,000 and $2,000,000 a year, depending on the type of program material. All programs broadcast to date have been sustaining programs—that is, the cost has been borne by the station owner. One reason is that the Federal Communications Commission has not yet issued any commercial station licenses under which the station owner could charge for sponsored programs. However, even if such licenses had been issued, it is unlikely that many sponsored programs would have been produced. The cost of such programs is so high that sponsors would be reluctant to pay for them until they were assured that they would reach a large number of people. On the other hand, the public will not buy receivers until more programs are available. This situation makes it necessary for the television-station owner to provide the programs, and it is quite understandable that he should be reluctant to incur the great expense necessary to give a more satisfactory service.

This situation is certain to improve in the relatively near future. In many cities, more than one television station will be in operation soon. With rival stations competing for program material, both the quantity and quality of television broadcasts are certain to be more satisfactory. The resulting increase in the number of receivers in operation will result in commercial sponsorship of programs becoming more attractive to the advertising profession, when such sponsorship is allowed by the Federal Communications Commission.

Public acceptance of television in the United States closely parallels that which occurred in England where there was at first great public interest, but few immediate sales of receivers. The increase in the number of receivers in the hands of the public was slow but steady until the time of the coronation of King George VI. Parts of this event were broadcast by television, and the results were so remarkably good that intense public interest was aroused, and the sales curve for television receivers turned upward sharply. In this country, the television industry is now in the period of slow but steady growth. Some special event of great public interest some day will be televised with a similar result on sales. The fact that several television stations will be on the air soon will hasten the arrival of this event.

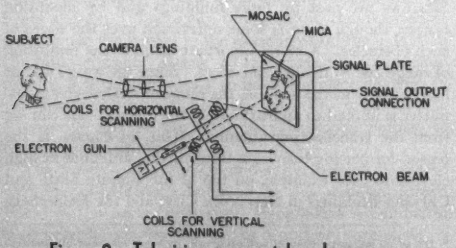



**Figure 2. Television camera tube—Iconoscope**

## Operating Principles

All electrical communication systems perform three essential functions: conversion of information into electric energy, transmission of this energy, and reconversion of the electric energy into a replica of the original information. In telephony, sound energy is converted into electric energy at the transmitter. The generated signals are then sent over wires to the receiver where the electric energy is reconverted into sound. In radiobroadcasting, sound energy is converted into electric energy at the microphone. After suitable modification, this energy is radiated into space at the antenna. In this case, transmission of the energy involves the use of electromagnetic waves. At the receiver, these waves are picked up. After suitable modification, the electric energy is retransformed into sound at the loud-speaker.

In television, these same three essential operations must be performed. The light energy reflected from a picture is first converted into electric energy. This energy is then modified and is radiated by the transmitting antenna, as in radiobroadcasting. At the receiver, the energy is picked up, remodified, and finally transformed into a replica of the original picture.

### PICTURE GENERATION

In photography, the image of a scene is focused on a photographic plate, and a chemical replica of the scene is formed on the plate due to photochemical effects. In television, the image of a scene is focused on the plate of a television-camera tube, and an electrical replica of the scene is formed due to the photoelectric effect. There are a number of different types of camera tubes, but it is sufficient to describe only one—the RCA Iconoscope.

The most important element in the Iconoscope is the image plate. This consists of a sheet of mica on the front side of which are deposited some 200 million minute cesium photoelectric cells. On the back side of the mica sheet is a metallic signal plate. Each cell is insulated from its neighboring cells and each element, in conjunction with the signal plate, forms a small capacitor. Because of its construction, the front side of the image plate is known as the mosaic. When a picture is focused on the mosaic, the photoemission of electrons takes place. These electrons are attracted to a positive collector ring, and in any given time each photoelement assumes a positive charge proportional to the incident illumination. Thus, the different light intensities in the picture are reproduced on the mosaic as variations in charge or in potential. In $1/30$ second, an element on which a strong light is falling assumes a potential approximately 1.5 volts positive with respect to an element in total darkness.

The remainder of the Iconoscope consists of means for transforming these space variations in potential over the surface of the mosaic into time variations in potential or into the "video" signal. This is accomplished by the process of scanning. An electron beam is generated in the electron-gun structure of the Iconoscope, and is moved rapidly across the plate in a series of nearly horizontal, parallel lines until the entire mosaic has been covered. When the electron beam strikes an element of the mosaic, it discharges the capacitor formed by the element and the signal plate, producing a current through the external load circuit. As the electron beam moves over the plate, it discharges each picture element in succession, producing currents instantaneously proportional to the charges on the various elements or to the incident illumination on these elements.

The motion of the electron beam in scanning is produced magnetically by means of currents in deflection coils. Two sets of coils are used, one to produce horizontal deflection of the beam, the other to cause vertical deflection. The deflection currents are approximately saw-toothed in shape with respect to time. Thus, the beam is moved across the mosaic at a uniform rate and is then returned quickly. The frequency of the currents in the horizontal deflection coils is 13,230 cycles while that of the currents in the vertical deflection coils is only 60 cycles. Thus, as the beam moves rapidly back and forth across the mosaic, it simultaneously moves slowly downward to cover the entire surface.

As soon as the mosaic is completely scanned, the electron beam returns to its starting point and repeats the scanning process. The mosaic is completely scanned in $^1/_{30}$ second. This is sufficiently rapid to produce the illusion of continuity of motion in the reproduced picture at the receiver, but is not fast enough to eliminate flicker. Flicker is eliminated by use of so-called interlaced scanning. Instead of scanning lines 1, 2, 3, 4, 5, 6 . . . in succession, lines 1, 3, 5 . . . are first scanned, then lines 2, 4, 6 . . . then 1, 3, 5 . . ., etc. The result is that the eye is fooled into thinking that it sees 60 pictures per second, and as a result no flicker is evident.

A very wide frequency signal band resultsf rom scanning. The minimum frequency is the frame frequency of 30 cycles. RMA television standards call for 441 scanning lines per picture, and for picture proportions of 4:3 aspect ratio (ratio of picture width to height). If a picture is divided into squares having sides equal to the distance between successive lines, 260,000 picture elements result. Each is scanned 30 times per second; or, 7,800,000 elements are traversed each second. The maximum signal frequency will be produced if alternate elements are black and white. Thus, the maximum frequency is nearly four megacycles. For good picture transmission a frequency band of four megacycles is required.

The video-frequency signals produced at the Iconoscope are treated in much the same manner that audio signals are treated in a radiobroadcast transmitter. They are amplified, used to modulate a carrier signal, and amplified further in a more or less conventional manner. Two important differences do exist. Since the video-frequency band is so wide, a television channel occupies considerable space in the electromagnetic spectrum. If double-side-band transmission were employed, a channel more than eight megacycles wide would be required. By transmitting only part of one side band, the channel width may be reduced to six megacycles, thus effecting considerable saving. Standard transmission-channel characteristics are shown in figure 3.

The high video frequencies necessitate much higher carrier frequencies than those required by sound broadcasting. The Federal Communications Commission has assigned 18 channels for television use. Of these, only the first 7 will be used in the immediate future for television-broadcast service. These channels are 50–56, 60–66, 66–72, 78–84, 84–90, 96–102, and 102–108 megacycles.*

### TRANSMISSION

The electromagnetic waves used in television transmission differ from those used in normal broadcasting only in frequency (or wave length). However, this difference results in significant differences in transmission characteristics. The antennas used in television are much smaller than those used at lower frequencies. For reception, a simple dipole—two rods each one-quarter wave length long placed end to end—is sufficient for most installations. For the first television channel, the over-all length

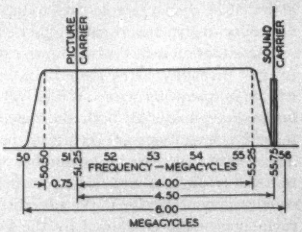



**Figure 3. Typical television - transmitter amplitude characteristics**

of such a structure is only ten feet. For transmission, more complex structures are used in order to obtain better impedance and directional characteristics. However, their dimensions are approximately the same as those of receiving antennas.

An important characteristic of high-frequency waves is their approximately straight-line propagation. In this, they somewhat resemble the much shorter light waves. Shadows are cast by large buildings and by mountain ranges, though there is some diffraction over the edges of such obstacles. A more important result is the limitation of range due to the horizon effect. Since the waves do not bend greatly at the horizon, the range of a television transmitter is limited to approximately the distance one can see from the transmitting antenna. This, of course, is the reason for placing television transmitting antennas at high elevations—for example, on top of the Empire State and Chrysler Buildings in New York City, and the Helderberg

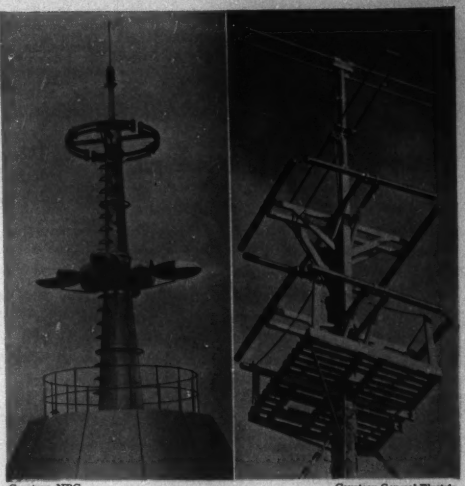
* The 44–50 megacycle channel now being used by some television transmitters will be used for frequency-modulation radiobroadcasting in the near future.

Mountains near Schenectady, N. Y. It should be noted that there is no sharp cutoff at the horizon. Up to a distance of approximately 15 per cent greater than the optical range, the field strength varies inversely as the square of the distance from the transmitting antenna. Beyond this distance, the field strength varies inversely as the third to fifth power of the distance, the exponent depending on the frequency.

Another important result of the quasi-optical nature of television transmission is the reflection of the waves from large vertical surfaces. Because of such reflections, waves may arrive at the receiver by more than one path. Any reflected path is longer than the direct path, and as a consequence reflected signals arrive later than direct signals. The result is the production of multiple images or echo pictures at the receiver. A difference in path lengths of 800 feet produces a displacement of the received pictures of $^1/_8$ inch on a 12-inch picture tube. The remedy for these echo effects is proper orientation of the receiving antenna or, if necessary, more elaborate receiving-antenna systems.

Television transmitters and receivers are connected to their respective antennas by means of transmission lines. If these lines are not properly terminated, reflections occur. The result is the production of echoes similar to those caused by multipath transmission.

The problem of interference is quite different from what it is on the standard broadcast band. True static interference does not exist. However, interference from automobile ignition systems and from the diathermy machines used by physicians is frequently very annoying. Television antennas are horizontally polarized to minimize ignition interference. No true fading exists, but a similar effect due to irregular reflections from moving objects, such as trucks or airplanes, may occur.



Courtesy NBC — Courtesy General Electric

**Figure 4. Typical television-transmitter antennas: left—sound and picture antennas of W2XBS atop the Empire State Building in New York City; right—combined frequency-modulation and television-sound antenna of W2XB in the Helderberg Mountains near Schenectady, N. Y.**

### PICTURE REPRODUCTION

The first portion of a television receiver is quite similar to the corresponding portion of a radiobroadcast receiver. The superheterodyne circuit is used almost exclusively in the United States. The function of the first portion of the receiver is to convert the received waves into a replica of the video signal produced at the camera tube by means of amplifiers, modulators, demodulators, etc. The video signal is converted into a picture by means of the picture tube. A typical picture tube or Kinescope (RCA designation) is shown in figure 7. This is essentially a high-grade cathode-ray tube with a grid for controlling the beam current. The light produced at the fluorescent screen upon the impact of the electron beam depends upon the beam current. Hence, to reproduce the transmitted picture, it is only necessary to move the electron beam in the Kinescope in synchronism with the beam at the Iconoscope and use the received video-signal voltage to control the beam current.

The process of picture reproduction may be compared with that of painting a design on the side of a clapboarded house with a paint spray gun. Each board is painted in succession by moving the gun at a uniform rate along its length from left to right. By controlling the pressure on the trigger of the gun, the amount of paint applied to any section of a board may be controlled. By exercising proper control of the trigger at all points along each board, any desired design may be painted.

Referring again to the picture tube, the electron beam is moved back and forth across the fluorescent screen in step with the electron beam in the Iconoscope at the transmitter; or, the fluorescent screen is scanned by the electron beam. The scanning is usually accomplished magnetically by saw-tooth currents in deflection coils as in the Iconoscope, although in small-diameter picture tubes electrostatic deflection by means of saw-tooth voltages applied to deflection plates is sometimes used. The number of electrons reaching any point of the fluorescent screen (and thus the brightness of that point of the screen) is controlled by means of voltages applied to the grid of the picture tube, as in a conventional vacuum tube. The grid voltage thus corresponds to pressure on the trigger of the paint gun.

The process of transmission of one element of a picture from Iconoscope to picture tube will now be traced briefly. Assume that the illumination of this element of the mosaic is high, corresponding to a high light in the picture. This section of the mosaic accumulates a positive charge due to the emission of photoelectrons. At the instant under consideration, the Iconoscope electron beam strikes this element and discharges it, producing a certain current in the Iconoscope output circuit and a positive voltage across a resistor in this (or in an associated) circuit. After amplification, modulation, transmission, amplifica-

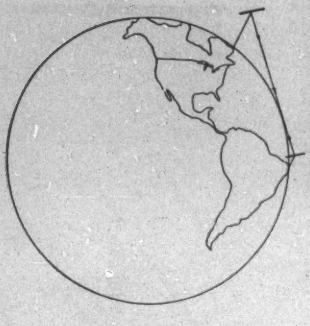


**Figure 5. Horizon limitation of ultrahigh - frequency - wave propagation**

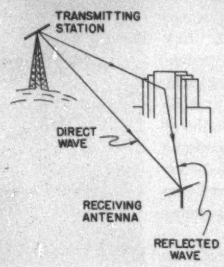



**Figure 6. Direct and reflected transmission paths**

tion, and detection, this positive voltage reappears on the grid of the picture tube. Circuits are so arranged that at this time, the electron beam in the picture tube strikes the screen at a position corresponding to that of the element of the mosaic under consideration. The positive voltage applied to the grid results in high beam current and a bright spot at the fluorescent screen. As the electron beams in the Iconoscope and picture tube move on together, the Iconoscope beam eventually reaches a picture element where very little light is falling. The resulting positive voltage in the Iconoscope output circuit is smaller than before. This reduced positive voltage appears on the grid of the picture tube, decreasing the beam current and producing a dark area at the screen. The process continues and the entire picture is reproduced, element by element.

### SYNCHRONIZING CHANNEL

It is evident that successful picture reproduction depends on keeping the motions of the electron beams at the camera tube and the picture tube synchronized. Otherwise the received picture will be hopelessly jumbled. This important function is performed by synchronizing signals which are transmitted along with the video or picture signals. They occur only during the retrace or return periods when the electron beam moves rapidly back from right to left or from bottom to top of the picture. The polarity and magnitude of these synchronizing signal voltages are such that they correspond to a fictitious light intensity more black than that corresponding to no light incident on the mosaic; or they are "blacker than black". Thus, the grid of the picture tube is driven more negative than the black level by the synchronizing signals, and these signals produce no extraneous picture. Since the synchronizing signals lie outside the voltage range used to represent light intensity, they can be separated from the picture signals by means of amplitude discriminating circuits and fed to the synchronizing circuits where they control the frequencies of the currents in the deflection coils. Two sets of synchronizing signals are used—one for horizontal deflection and one for vertical deflection. The two sets of synchronizing pulses differ from each other in duration and are usually separated from each other by differentiating and integrating circuits. Figure 8 shows a portion of a typical composite signal consisting of video and synchronizing signals.

### SOUND CHANNEL

Every television picture transmitter has associated with it a complete radiobroadcasting station to transmit the accompanying sound. Likewise, every complete television receiver has a sound channel to receive this sound. The circuits are arranged so that both picture and sound channels are tuned simultaneously.

Since plenty of frequency space is available, the sound channel is always of high fidelity. The high audio frequencies are pre-emphasized at the transmitter, allowing a drooping frequency characteristic at the receiver. The result is that the increase in noise due to high-fidelity operation is much less than normal.

A complete television system embodying picture, synchronizing, and sound channels is indicated in figure 9.

## Some Common Questions

There are a number of questions that are commonly asked regarding television. Some of these already have been discussed. Others are considered in succeeding paragraphs.

### RANGE

The limitation of consistently good television service to an area having a radius not greatly exceeding the optical range from the transmitting antenna is of a fundamental nature, since it depends upon the properties of high-frequency electromagnetic waves. There seem to be only two possibilities of extending the range. The first of these is the use of frequency-modulated transmitters. Although the field strength of frequency-modulated waves varies with distance from the transmitter in the same manner as does that of amplitude-modulated waves, the useful range is greater because a much lower signal-to-noise ratio is required, and hence reception is possible with lower signal strengths.

The second possibility is the development of some radically different method of picture transmission which might conceivably be used over longer distances. No such development is in prospect at the present time.

It may be concluded that the range of consistent television transmission is definitely limited. Even the use of frequency modulation would not greatly increase the range. Hence, for some time to come, television service will be confined to areas within, say, 30 to 60 miles from transmitters. These transmitters will be located only near large centers of population.

Transmission over greater distances is always the result of either very elaborate receiving systems or freak condi-

tions. At the General Electric Company station W2XB near Schenectady, N. Y., pictures from W2XBS in New York are consistently received. However, the receiving antenna is a large rhombic antenna located in the Helderberg Mountains at a height of 1,828 feet above sea level. Such facilities, of course, are far superior to those available to the average owner of a television receiver. Pictures from the London television transmitter have been received on Long Island, N. Y., by the Radio Corporation of America. This, however, is a case of freak transmission which cannot be relied upon for regular reception. Such freak transmissions, however, may cause annoying interference with reception from nearby stations.

### CHAIN TELEVISION BROADCASTING

It is probable that in the relatively near future, television stations will be linked into networks comparable to present-day radiobroadcasting networks. However, the method of connecting the various stations will be much different.

Because of the wide frequency band required for transmission of high-quality television pictures, telephone lines are suitable only for extremely short-distance transmission and then only with the use of elaborate correction networks. The transmission loss over one mile of telephone distribution cable increases from 25 decibels at 0.5 megacycles to 68 decibels at 3 megacycles. Moreover, the phase characteristics are far different from the desired linear variation of phase shift with frequency. Transmission has been accomplished over distances of approximately a mile, but long-distance transmission is highly improbable.

Coaxial cable may be employed to link television transmitters, but its cost is prohibitive when long distances are to be covered. The solution of the problem is the use of ultrahigh-frequency television transmitters as relay stations. These will be located every 30 or 50 miles along the desired route and will probably consist of a receiving antenna, amplifier, and transmitting antenna. The stations will be entirely unattended. Carrier frequencies of several hundred megacycles will be used. Preliminary tests have shown that such relay stations are entirely practicable.

### TELEVISION RECEIVERS

Three classes of receivers are recognized in the television industry. A "picture receiver" will receive pictures only and has no facilities for receiving the associated sound. A "picture receiver with sound converter" has, in addition, an incomplete sound channel requiring the use of an auxiliary sound receiver. A "television receiver" has complete channels for both the picture and the associated sound. Expensive television receivers usually have included in the same cabinet a complete radio receiver.

The diameter of the picture tube determines the picture size. At present, receivers are available with tubes having diameters of 5, 7, 9, 12, and 14 inches. The ratio of picture-tube screen diameter to picture width to picture height is 5:4:3. Large diameter tubes are usually quite long, and it is awkward to build cabinets of the depth required to accommodate them in a horizontal position. Hence, such tubes often are mounted vertically and the picture is viewed in an inclined mirror. Smaller tubes are mounted horizontally for direct viewing.

The operation of a television receiver is not particularly complex. Station selection usually is accomplished by means of push buttons. In addition, a vernier tuning control often is provided. When this is tuned for maximum sound, the picture automatically is tuned correctly. Contrast and brightness controls allow the user to adjust the gain of the receiver and the average brightness of the picture. Other picture channel controls do not have to be adjusted frequently and are often located where they are easily available to the service man, but not to the user. The controls on the sound channel are the same as on ordinary radio receivers.

### COST AND OBSOLESCENCE OF RECEIVERS

In considering possible price reductions in television receivers, a brief study of prices in England is instructive. Prices of English and American receivers are listed in

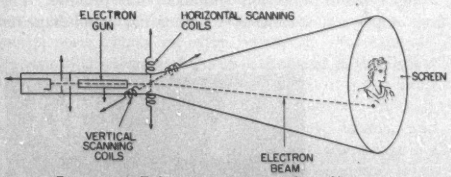



**Figure 7. Television picture tube—Kinescope**

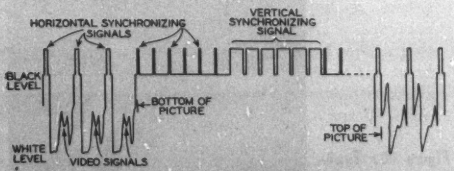



**Figure 8. Portion of complete composite video and synchronizing signal at bottom of picture**

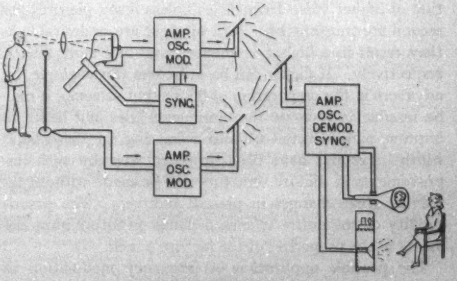



**Figure 9. Complete television system**

AMP.—Amplifier DEMOD.—Demodulator
OSC.—Oscillator MOD.—Modulator SYNC.—Synchronizer

**Table I. Prices of English and American Television Receivers**

| Country | Year | Price (Dollars Per Inch of Diameter of Picture Tube) |
|---|---|---|
| England | Fall, 1936 | 35 to 44 |
| | Fall, 1937 | 21 to 37 |
| | Fall, 1938 | 20 to 37 |
| | Fall, 1939 | 16 to 21 |
| United States of America | Summer, 1939 | 40 to 50 |

table I. Since the price of a television receiver is largely a function of the diameter of the picture tube, the prices are given in dollars per inch of diameter of that tube. It may be seen that in three years, English receivers were reduced in price approximately 50 per cent.

Prices in America may always be higher than in England. In America, receivers must be built to receive several stations, while in England the government monopoly of communications prevents the establishment of more than one station in any locality. English standards limit the maximum detail available in a picture to a lower value than do the standards in the United States, with the result that certain economies can be effected in English receivers which cannot be made in American receivers.

The question of obsolescence of receivers is closely related to the matter of television standards of transmission. The present RMA television standards provide satisfactory television service. This, however, is no reason for arguing that the art must stagnate at its present level. Such improvements as can be justified from engineering and economic standpoints should be introduced. The Federal Communications Commission, while recognizing the value of the present standards, has steadfastly refused to approve them as the final answer to all the problems of television broadcasting.

One direction in which the art may progress is toward greater picture detail. The present RMA standards provide an admittedly sufficient amount of detail in pictures produced on 12-inch tubes. There is a feeling among some in the industry that this detail will not be sufficient when larger pictures are viewed at close range. The maximum detail is a function of the number of scanning lines per picture. The detail cannot be increased without the production of higher video frequencies unless fewer pictures per second are transmitted. Both of these are undesirable as they result in a higher frequency band and more flicker, respectively. If flicker can be overcome (for example, by advances in the preparation of fluorescent screens), it may be feasible to increase the number of lines and hence to improve picture detail without increasing the video band width. Systems have been proposed whereby such improvements in picture structure can be made without involving great changes in present receivers. The practicability of the entire scheme depends on future improvements in the properties of the picture screen.

The possible application of frequency modulation to television already has been mentioned. Various proposed television systems employ frequency modulation for the sound channel, for the synchronizing channel, for the picture channel, and for all channels. Such systems might have advantages over amplitude-modulation systems other than improved freedom from noise. In sound broadcasting, a deviation ratio (maximum excursion of carrier frequency to maximum modulating frequency) of five to one seems desirable. This would require a total band width of 40 megacycles for television broadcasting using a maximum video frequency of 4 megacycles. This, of course, is prohibitive except at extreme ultrahigh carrier frequencies. The alternative is to use a lower deviation ratio, say one to one. Whether the full advantages of frequency modulation are obtained with low deviation ratios is a matter upon which agreement has not been reached. It is probable that amplitude modulation will be retained on the first seven television channels. When carrier frequencies above 150 megacycles are used for television broadcasting, it is quite probable that frequency modulation will be employed. This probably will not occur for several years.

### LARGE PICTURES

The diameter of the picture-tube screen cannot be increased indefinitely because of mechanical limitations. An experimental picture tube having a diameter of 31 inches was once constructed by RCA. This tube was $4\frac{1}{2}$ feet long. A convex Pyrex face, two inches thick, was required to withstand the five tons of atmospheric force. Such a tube obviously is unsuited for home use.

The practical production of large pictures necessarily involves some projection scheme. The principal problem is the production of a picture of such high brightness that the brightness of the enlarged projected picture will be satisfactory. Motion-picture practice aims at a screen brightness of approximately 3.5 candles per square foot, although 1.5 candles per square foot is about the present average. The brightness of the high lights in directly viewed television picture tubes is approximately 6 candles per square foot. Hence, these do not permit of much enlargement.

Four types of projection equipment offer promise. The first employs a somewhat conventional small-diameter

**Figure 10. Typical television receiver**

picture tube operated at very high second-anode voltage. The chief difficulties are with screen life and in the electron optics involved in the design of an electron-gun structure to produce a sufficiently fine electron beam. A projection lens is employed to enlarge the picture. Screen brightnesses of the order of one candle per square foot on a screen ten feet wide have been obtained.

The second type of projection equipment is that developed in England by Scophony. This employs an entirely different type of equipment involving mechanical elements rotating at high speed and a supersonic light valve (*EE April '40, p. 151*). Other proposed projection systems employ intermediate motion-picture film and special types of thermally or electrically sensitive picture-tube screens. These systems have not yet proved practicable.

No American manufacturer has yet placed projection-type receivers on the market. However, they may be available within the next few months. Projection equipment, of course, is necessary if television is ever to be shown in theaters. Such television service would doubtless be of a supplementary nature only, offering theater patrons the facilities for viewing news or sports events of special interest.

### PICTURE COLOR

Television pictures are produced in black and white only. All picture-tube screens are not the same and the "white" may be slightly off on the yellow (warm) or blue (cold) side. Television systems for showing pictures in natural colors have been the subject of many patents, and of some laboratory investigation. The introduction of any natural-color system into practical television broadcasting lies far in the future.

### PROGRAMS

In New York City, station W2XBS broadcasts television programs approximately 15 hours a week. A great variety of programs has been produced. These include drama, opera, variety shows, news comments, fashion shows, art-appreciation programs, hobby exhibits, puppet shows, ballet performances, cooking demonstrations, etc. Special news events are often broadcast. For example, the visit of the King and Queen of England to the United States was well covered. Sporting events of many kinds have been transmitted. These include baseball, football, basketball, tennis, horse racing, hockey, boxing, and wrestling. It has been remarked that if the best seat in a football stadium sells for $3.30, the television picture is the equivalent of a $1.65 seat.

In radiobroadcasting, many programs are presented by means of recordings or electrical transcriptions. Motion pictures are the analogous subject matter in television, with newsreels and cartoons being the most popular presentations. Special equipment is required at the transmitter to compensate for the different frame frequencies used in motion pictures and television (24 and 30 frames per second).

For remote pickups, as used for special news events, sports, etc., a complete portable television transmitter is taken to the desired location. It transmits the program on an ultrahigh-frequency link, usually 156 to 162 megacycles, to the main studio where the program is received, monitored, and rebroadcast.

### MISCELLANEOUS USES OF TELEVISION

The chief use of television is for entertainment. However, other applications may be of great future importance. For example, the educational possibilities of television, especially in the field of art, must not be overlooked. In many cities, instruction via radio is a regular feature of

**Table II. Licensed Television Transmitters**

| Location | Call Letters | Owner |
|---|---|---|
| **Broadcasting on Regular Schedule** | | |
| New York, N. Y. | W2XBS | National Broadcasting Company |
| Chicago, Ill. | W9XZY | Zenith Radio Corporation |
| Los Angeles, Calif. | W6XAO | Don Lee Broadcasting System |
| **Broadcasting Experimentally** | | |
| New York, N. Y. | W2XAB | Columbia Broadcasting System |
| Passaic, N. J. | W2XVT | Allen B. DuMont Laboratories |
| Helderberg Mountains near Schenectady, N. Y. | W2XB | General Electric Company |
| Philadelphia, Pa. | W3XE | Philco Radio and Television Corporation |
| **Under Construction or Design** | | |
| Boston, Mass. | W1XG | General Television Corporation |
| Bridgeport, Conn. | W1XA | General Electric Company |
| New York, N. Y. | W2XWV | Allen B. DuMont Laboratories |
| Long Island City, N. Y. | W2XDR | Radio Pictures |
| Camden, N. J. | W3XEP | RCA Manufacturing Company |
| Iowa City, Ia. | W9XUI | State University of Iowa |
| Kansas City, Mo. | W9XAL | First National Television |
| **Ultrahigh-Frequency Stations** | | |
| New York, N. Y. | W10XKT | Allen B. DuMont Laboratories |
| New York, N. Y. and Camden, N. J. (portable) | W2XBT | National Broadcasting Company |
| Camden, N. J. (portable) | W3XAD | RCA Manufacturing Company |
| Philadelphia, Pa. | W3XP | Philco Radio and Television Corporation |
| Schenectady, N. Y. | W2XH | General Electric Company |
| Los Angeles, Calif. | W6XDU | Don Lee Broadcasting System |
| **Low-Definition Experimental Stations** | | |
| West Lafayette, Ind. | W9XG | Purdue University |
| Iowa City, Ia. | W9XK | State University of Iowa |

**Table III. Television-Station License Applicants**

| Location | Applicant |
|---|---|
| Boston, Mass. | Boston Edison Company |
| Springfield, Mass. | Henry Walczak |
| Avon, Conn. | Travelers Broadcasting Company |
| Meriden, Conn. | WDRC, Inc. |
| New York, N. Y. | Columbia Broadcasting System |
| | Bamberger Broadcasting Service |
| | Metropolitan Television (Bloomingdale Brothers and Abraham and Straus, department stores) |
| Philadelphia, Pa. | National Broadcasting Company |
| | WCAU |
| Washington, D. C. | National Broadcasting Company |
| | Allen B. DuMont Laboratories |
| Cincinnati, Ohio | Crosley Radio Corporation |
| Fort Wayne, Ind. | Farnsworth Television Corporation |
| Chicago, Ill. | National Broadcasting Company |
| | Balaban and Katz |
| Milwaukee, Wis. | Milwaukee Journal |
| St. Paul, Minn. | KSTP, Inc. |
| Des Moines, Iowa | R. B. Eaton |
| Kansas City, Mo. | Midland Broadcasting Service |
| Manhattan, Kans. | Kansas State College |
| North Sacramento, Calif. | Grant Union High School |
| San Francisco, Calif. | Don Lee Broadcasting System |
| | Hughes Tool Company |
| Los Angeles, Calif. | Earle G. Anthony, Inc. |
| | Hughes Tool Company |
| | Leroy's Jewelers |
| | May Department Stores |
| | Television Productions |

public school work. This work could be greatly expanded by the use of television.

Television is undoubtedly of military value. The recent feat of the National Broadcasting Company of broadcasting a television program originating in portable transmitting equipment carried in a moving airplane indicates possible military uses.

Science doubtless will find television a valuable tool. Mention must be made of recent studies of the corona of the sun, which were made possible only by the application of the principles of television.

### PRESENT STATUS OF TELEVISION BROADCASTING

At the present time, only three television stations are providing regularly scheduled entertainment programs. These are W2XBS in New York, W9XZY in Chicago, and W6XAO in Los Angeles. This last station has been broadcasting television programs since 1933, but has been operating on an experimental basis until recently. In addition to these stations, 19 others in 12 cities have been licensed by the Federal Communications Commission. All licensed stations are listed in table II in which the status of each station is indicated. Applications for licenses for at least 28 other television transmitters in 20 cities have been filed before the Commission. These are listed in table III.

Several licensed stations are preparing to broadcast commercially sponsored programs. This matter has been the subject of heated debate before the Federal Communications Commission, which announced on February 29, 1940, that limited commercial sponsorship would be allowed after September 1 and then, on March 23, rescinded this order and held further hearings. On May 28, the Commission ruled that for the present, all television transmitting stations should confine their activities to research and development work and should not proceed with plans for immediate expansion of program service. This ruling is subject to review in the fall of 1940. This action of the Commission will delay the extension of public television service, but may possibly result in the industry building on a basis that will prove to be more permanently satisfactory.

# Norman W. Storer — 1939 Lamme Medalist

***"For meritorious achievement in the development of apparatus and machinery for electrical transportation"***

THE AIEE Lamme Medal for 1939 was presented during the Institute's recent summer convention at Swampscott, Mass., to Norman W. Storer (A'95, F'13) retired consulting railway engineer of the Westinghouse Electric and Manufacturing Company.

Opening the presentation ceremonies Doctor W. B. Kouwenhoven (A'06, F'34) chairman of the Lamme Medal committee, said:

"This year marks the 12th presentation of the Lamme Medal. It is interesting to note that the first award of the Lamme Medal was made at Swampscott on June 26, 1929, almost 11 years ago to the day. The medalist of that year was Allan B. Field. It is also of significance that the man who at that initial presentation of the medal gave a sketch of Mr. Lamme's career is the man whom we are gathered to honor on this occasion.

"Mr. Lamme, the founder of the medal, was born on an Ohio farm in 1864. He had a natural bent for mechanical devices and was fascinated by mathematics. He graduated from Ohio State University in 1888 and in the following year began his work in the test department of the Westinghouse Electric and Manufacturing Company. In 1924, when he died, he was its chief engineer.

"His vast contributions to the design and development of electrical machinery are marked by his inspirational force and his achievements as the guiding genius of the company with which he was associated. Mr. Lamme possessed a brilliant mind. His industry, his courage and his imagination were outstanding. He was a pioneer in a field in which little was known. He was interested in young men and their further education after leaving college. He was a great man of broad vision.

"He realized the need for inspiration and incentive and in his will established three medals. One, at Ohio State University, is awarded "for meritorious achievement in engineering or the technical arts". It is of interest to note that Mr. Storer received the Ohio State Lamme medal in 1933. The second is awarded by the Society for Promotion of Engineering Education, "for accomplishments in technical teaching or actual advancement of the art of technical training". The third is the AIEE medal, "for meritorious achievement in the development of electrical apparatus or machinery."

"It is the Lamme Medal of the Institute that we are awarding today. This medal will continue to serve as an inspiration and as a guiding star to the engineers of the future."

Medalist Storer's career was reviewed by Doctor A. M. Dudley (A'08, F'13) Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., after which President F. Malcolm Farmer made the presentation. Essential substance of Doctor Dudley's informal remarks and of Mr. Storer's response, as recorded at the meeting, follows.

# N. W. Storer—A Personal Tribute

A. M. DUDLEY, Fellow AIEE

In the very fertile country of the great nation of the Buckeye, where the sweeping curve of Lake Erie cuts across the western boundary line of Pennsylvania, the county in Ohio is Ashtabula, the most northeastern county. Just below Ashtabula is Trumbull County; and in a little town on the edge of Pennsylvania called Orangeville, Norman W. Storer was born. This little town is so situated that when you retire at night you can hang your clothes in Ohio and go to bed in Pennsylvania if you so desire.

It has not been told us whether Mr. Storer climbed any telegraph poles when he was young, or what he did, but we have it on good authority that he got through the public-school system of Ohio and went to Ohio State University, where in 1891 he graduated with the degree of mechanical engineer in electrical engineering. That degree has not been hailed with joy by either electrical or mechanical engineers, but in this case it was distinctly prophetic, because the work which Mr. Storer has done, the marvelous engineering job, has been quite as much, I think, on the side of mechanical engineering as on that of electrical engineering.

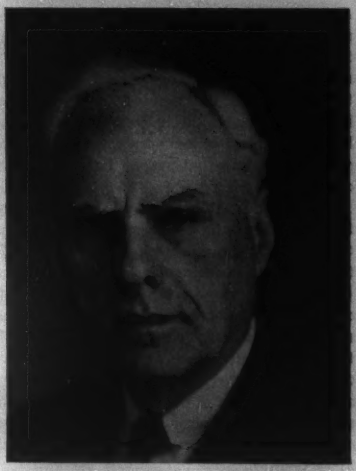
There has been a grand group of Buckeyes coming from that commonwealth. I think some good historian will have to write the history of that group and tell the debt that the Westinghouse company and the engineering profession and the AIEE owe to such men as Stillwell and Lamme and Storer and Mershon and Skinner and Paul Lincoln and Scott and others.

When Mr. Storer came to the Westinghouse company in 1891 after his graduation, he says there was no student course, but they allowed him to go out into the shop and wind coils. So he wound coils for a short time and then he was asked by Mr. Lamme to run the original series of tests on the old number three railway motor. The number three railway motor to us Westinghouse men was the first single-reduction railway motor with a series winding upon the armature. And Mr. Storer, who says that this was one of the most interesting jobs that he ever had, was apparently so intrigued by applications of transportation in engineering that he stayed pretty well with it ever since.

Since Mr. Lamme gave the medal and Mr. Storer is receiving it, I thought it would interest you to hear a little quotation directly from Mr. Lamme at this particular period. Mr. Lamme was speaking not of a railway motor, but of a four-pole, ring-type generator-armature winding, in the days when there were no slots on the armatures and the winding had to stay right on the cylindrical core and sometimes after short-circuit shifted as much as three or four inches. Mr. Lamme asked Mr. Storer to attempt this job of winding, of which he said:

"This was one of the first jobs that was assigned to Mr. N. W. Storer. Regular winders did not think the construction possible, so we had to put on this work some man who was not so sure that it could not be done."

Another very interesting thing I found that Mr. Lamme said about Mr. Storer occurred about two years later, in 1893, when Mr. Storer was helping Mr. Lamme with the early development of the induction motor. Mr. Lamme said, "At the conclusion of the test Mr. Storer burnt off the insulation of the rotor end windings and then soldered both ends of his secondary windings solidly together in order to make the equivalent of a cage which also gave very good results." This, therefore, was the first real squirrel-cage motor in our early tests. Those men of you who have always thought that Mr. Storer was direct current without any alternating current will be pleased to know that he was in on the early development of the induction motor.



Norman Wilson Storer

Dividing Mr. Storer's career into periods, the first is that from 1891 to 1904, when he was Mr. Lamme's first assistant. During that time he developed a line of d-c motors and generators. It is interesting to note that he speaks very highly of the contribution of Miss Bertha Lamme as his assistant at that time. She was the sister of B. G. Lamme.

During that period there were two things that were outstanding that Mr. Storer did, I think. One of them was the root-mean-square system of rating railway motors. At that time the pioneers had very little to go on. I was looking the other day at a photograph of a double-reduction railway motor with a huge cast-iron yoke around it. It looked nothing at all like our present motors, and the nominal or one-hour rating did not mean a thing, because the motors would not even run an hour idle at full voltage. That's quite true on account of the iron loss; it sounds funny but it was true anyway. But Mr. Storer, who perhaps knew about the root mean square—that is, figuring out for the different periods of the cycle that the motor operated what current was required, squaring them and multiplying by the time and dividing by the total time

and extracting the square root—got the so-called root-mean-square current or rating. But he also realized that the iron loss must be made consistent with that, so he adopted the system of operating the motor on test at 300 to 400 volts. At that nominal rating at that voltage it did have a continuous rating. The combination of the iron loss and the copper loss very closely simulated the actual performance and that system has been universally used ever since.

The second achievement is his contribution to the thinking about the inertia of the rotating parts of the truck and of the motor itself to the tractive effort required to accelerate the entire combination.

Mr. Storer himself said about that, "Up to that time no consideration had been given to the energy that had to be stored in the wheels, gears, axles, and especially the armatures in accelerating them. I found that in the cars of that date the energy due to rotation of these parts was about ten per cent of the energy stored in the dead weight, making a total requirement of 100 pounds per ton to accelerate a car at one mile per hour per second, instead of $91^{1}/_{10}$ pounds."

Doctor C. F. Scott says that the first Institute paper that Mr. Storer delivered in 1902 was on that particular subject.

The next period of Mr. Storer's work is that from 1904 to 1912, when he was division engineer of the railway engineering department, entrusted with the sole responsibility for the development and the design and the operation not only of motors, but of control-line equipment and locomotives over the entire period. Those of us who lived through that time can remember what happened there; it was something like this: Main-line electrification of steam railroads really got under way. There were developed a-c d-c passenger locomotives, geared and gearless. The New York, New Haven, and Hartford electrification, in itself one of the mile posts in transportation development, occurred in this period. The third-rail d-c locomotive for the Pennsylvania Terminal, a-c freight locomotives of several types, and the New Haven switcher locomotives, a-c locomotives for St. Claire Tunnel and the Hoosac Tunnel were all developed. Commutating poles were first put in railway motors introducing speed control and used in the New Haven d-c zone, in the Pennsylvania Terminal locomotives, and in light tracks generally; and also 1,500-volt locomotives for the Piedmont and Northern Railway. All these were crowded into eight years and the responsibility for them rests on the man we are talking about today.

I might say that when they electrified the New Haven, they undertook one of the toughest problems that possibly ever could arise, because both the New York Central locomotives which operated on 600 volts direct current and the New Haven locomotives which operated on 11,000 volts alternating current had to run off the same trolley going into the Grand Central Terminal. That again illustrates the versatility of the man we are talking about.

In this period the particular achievement of Mr. Storer's that I want to speak about is the development of the quill-drive twin motor. Even on high-speed passenger locomotives, the direct-connected motor—that is, the one operating on the axle—was very slow speed. Mr. Storer says that in developing a higher-speed motor of practically double the speed he found that it had only about 50 per cent more horsepower on account of the increased width of the pinion, so that he conceived the idea of making twin motors operating through a quill—a drive which is practically universal in the world today for high-speed passenger service. It gets at once the higher speed, the smaller armature with less inertia, the double-voltage and half-

AIEE Lamme Medal

current effect; and even the pinion face itself being less gives room for wider cores, so that the whole thing was a gain all the way through.

The next period was from 1912 to 1926, when Mr. Storer was general engineer specializing on railway problems. In this period came up single-phase motor-generator-type locomotives, such as were used on the Detroit, Toledo, and Ironton when Mr. Ford went into the railway business; also the Great Northern electrification, where the frames of the motors were an integral part of the locomotive frames. Also high-voltage direct current came up for consideration quite prominently at that time. Those of us graceless youngsters who operated at that time about ten years behind Mr. Lamme and Mr. Storer got a lot of fun out of egging them on to debate the relative merits of single-phase alternating current and high-voltage direct current for traction purposes. You may have heard so much of that joke that perhaps you think there was a rift in the Westinghouse policy at that time, but there was not. Either man would have used the system that was best for the job he had in mind, but we used to get them to arguing.

During this high-voltage discussion we made mention of 1,500 volts for Piedmont, and then very soon of 3,000 volts for the Chicago, Milwaukee, and St. Paul. There again Mr. Storer's mechanical engineering as well as his electrical came into play, because he and Mr. Eaton, working together, produced locomotives which for mechanical balance were very beautiful and did the job that they had to do.

Also there came up another very interesting thing. Some of you may not have known that there was once a 5,000-volt d-c commercial application in this country. It was at Grass Lake, just outside of Jackson, Mich. It ran for two years and Mr. Storer designed the motors and the control. It was interesting from another point of

view, because it involved a mercury rectifier, a rectifier not in the locomotive but in the substation.

(I like to think that in giving the medal Mr. Lamme wanted to perpetuate the kind of engineering that he knew best and did best, and that nothing would have given him more pleasure than to have seen it bestowed on Mr. Storer, who is a man after his own heart.)

The last period, from 1926 to 1936, Mr. Storer was consulting engineer and I think particularly of two projects that he worked on, one of which was connected with Diesel-electric propulsion, showing that he was coming right along up to date. The other was a byway, a very interesting system which you may have heard him describe. It consisted of three platforms side by side, one stationary and one running about 22 miles an hour and an intermediate one which periodically slowed down to a standstill and then speeded up to the speed of the third one. Thus you can move an enormous number of people who just step from the stationary platform onto the intermediate and finally onto the high-speed platform. Now that is interesting because it connects Mr. Storer with the New York World's Fair in 1939–40. The induction motors he was working on in 1893 were exhibited at the Chicago World's Fair in that year, and his byway very closely approximates the "futurama" of General Motors. This man whose engineering career lasted 45 years touched two World's Fairs that were 46 years apart, and touched them very actively.

So much for Mr. Storer's career. But what about Storer the man? When I first saw him in 1904, I thought that in personal appearance Mr. Storer was the most distinguished member of the clan Westinghouse and I never have had any occasion to change my opinion.

He is a man of considerable physical strength. He likes games that involve muscular effort. My memory slows me down again by reminding me that when the Pennsylvania Terminal was electrified Mr. Storer and Mr. Eaton were down there working on the job and they had an idle moment and on one of the six-foot platforms they indulged in a little knee-and-elbow wrestling; that kind of wrestling in which you take the other man's hand and put your foot and your knee against his and then see which can upset the other. And thereby the Westinghouse company nearly lost a perfectly good chief mechanical engineer, because Mr. Eaton departed hastily and landed on the tracks down below.

Mr. Storer is just as good as he looks in many other ways. He is as good as he looks in moral character, in sense of humor, and in rugged honesty that believes in fighting for what is worth fighting for. In his civic and social interests he has been very broad. He is a man of real culture, the best kind of culture. I wish those who haven't noticed or haven't carefully read Doctor Parker's article on "This Culture" in the June issue of ELECTRICAL ENGINEERING would get and read it, because it is very elegantly expressed as English goes, and it sets forth the dictum that beautiful engineering material handled by great teachers can give us as much culture as we could possibly get in any other way. He mentions, not by name, some of the great teachers that he and I both had at the University of Michigan. I really think, without trying to hand this culture business back to the educators, that it is possible to get real culture out of engineering.

I should like to pay my own personal tribute to Mr. Storer, who inspired me and steadied me as a young man. He was about ten years older than I was, and ten years wiser in professional experience; a man who is hero-worshipped. Tentatively I at first started to call him "Uncle Norman." After a while I got a little bolder and called him "Norman"; he has been "Norman" to me ever since and he has done a lot of things for me. So I give you, for the Lamme Medal, that grand pioneer engineer, that matchless good citizen, that unavowed chieftain of the great Buckeye nation, Norman Wilson Storer.

## Medalist Storer's Response

I appreciate deeply the honor that has been conferred upon me. It is all the more pleasing to me because of my close association with Mr. Lamme many years ago.

It was from 1891 up to 1924 that I was very close to Mr. Lamme. We didn't fight over alternating current or direct current. Lamme wouldn't discuss it with me. I think he was a little afraid. But he said, "Well, we've got to make this a-c stuff; we got started on it." I gave him 5,000 volts direct current, but that was too high. They didn't need such high voltage. But I can assure you that with either alternating or direct current on the trolley you can do any piece of railway electrification work which is to be found in the country, and then some.

But after all the pioneer work and all we have passed through it is disappointing to the engineers to find that so little has been accomplished in the percentage of railways electrified in this country. It is far too small, and especially at a time like this.

A year ago, a little over, I listened to a very interesting lecture by Colonel W. J. Wilgus, delivered at a little University Club powwow down in Winter Park, Fla. Colonel Wilgus called the railways our first line of defense and in order to make it safe for the country he proposed that the government should own all of the railroads and operate them under one head.

I am not going to go any further than that. That statement was well backed up by Colonel Wilgus. But right now, I think we have got to mind our p's and q's; get our railways system in good operation, as well as battleships. Colonel Wilgus said in effect, "If you don't have the transportation—railway transportation, you might just as well take the battleships out and sink them."

There is one thing that I wanted to say about this medal. I feel embarrassed in receiving as much credit as Doctor Dudley has handed out. I think that it ought to be recognized that I am only one out of many who have been mixed up in all these propositions and a great deal of credit goes to those who worked with me on the job. I had some of the most loyal and best men working with me on all those jobs that I ever came across, and I want to give them full credit.

# Of Current Interest

## Industry • • • •

### EEI Adopts Preparedness Resolution

During its eighth annual convention, the Edison Electric Institute at Atlantic City on June 5, 1940, unanimously adopted the following resolution as representing the attitude of the electric-utility industry of the United States:

WHEREAS, Our Government is taking steps to assure the speedy strengthening of our national defense, and

WHEREAS, this will require the expenditure of billions of dollars of public funds which must be reflected in added public debt and increased taxes, and

WHEREAS, it should be the function of private capital to provide, so far as practicable, for the financing of industrial needs and expansion of facilities in this emergency to the end that government funds may be released for those things which only government can do, and

WHEREAS, the electric light and power industry, built up in this country through the past sixty years by private capital and individual initiative and now supplying 90 per cent of the electric public-utility service of this country, is able and anxious to do its full part in this hour of national emergency, and

WHEREAS, for the manufacture of munitions of war the electric utilities of this country have a great responsibility in the supplying of adequate electric power to those industrial establishments which depend upon central-station service, and

WHEREAS, the electric utilities are presently prepared with and will maintain ample plant facilities and the trained, experienced, and efficient organizations required to discharge this great responsibility;

BE IT RESOLVED that the members of the Edison Electric Institute, in convention assembled, express their willingness and readiness to devote their full capabilities, their best efforts, and their resources to aid our country by continuing to maintain an ample supply of electric power for war industries.

In his presidential address to EEI conventioneers, EEI President C. W. Kellogg reminded his listeners of the following pertinent facts:

"Since a large part of American industry is electrified, an adequate power supply to turn the wheels of industry is a basic necessity of the country. Although many industrial establishments have their own power sources, still the electric utilities supply about three-quarters of all the electric power used by industry in this country and therefore face a great responsibility in the present situation. They can face it, however, with complete confidence, for they are prepared with the requisite plant facilities, experienced organization and personnel, and existing sound business relationships, to meet the responsibility. Never in history has any country been so well equipped with power for the production of munitions as is our country today. Let us consider some of the more important factors which verify our state of preparedness.

"At the end of 1939 installed generating capacity in the United States exceeded the sum of the noncoincident peak demands on our power stations by over 40 per cent. In the industrial areas of the nation, where the munitions of war would be produced, this margin was 39 per cent. Effectively this margin is even greater, due to the network of interconnection between power plants and power systems, the diversity of whose requirements makes the combined instantaneous peak demand substantially less than the sum of the noncoincident peak demands.

"The utility industry will add 1,640,000 kilowatts of generating capacity in 1940 and a further million and a quarter kilowatts of generating capacity is already planned for completion in 1941; still more can be provided if conditions require to keep ahead of the normal rate of growth and maintain the margin. A large part of this new capacity is to be in steam plants, located in the industrial areas. In addition, in 1940 the Federal Government will add 230,000 kilowatts of generating capacity in the TVA and other areas.

"Ample power capacity is available to supply all the existing industrial establishments of the United States. Incremental new power capacity can be added just as fast as new munitions factories could be built.

"The power industry now has three and a third times as much generating capacity, and an annual output of electric energy four times as great, as in 1917, when we entered the World War. True, we have taken on much greater responsibilities in supplying power to industry since that time, but the amount of generating capacity in isolated industrial power plants has remained about the same from 1917 to date. In the meantime, while we have gained in capacity 230 per cent and in output 300 per cent, the corresponding gain in population has been only 29 per cent; and the gain in industrial production, as measured by the output of all kinds of factories, is about 15 per cent."

### Experiments With Radiotelephony for Freight Trains Authorized

The Central Railway Signal Company of Proviso, Ill., has been authorized by the Federal Communications Commission to experiment in radiotelephone communication between the central control tower of a railroad freight yard and locomotives therein. The FCC issued to the company construction permits for two Class II experimental stations at Proviso, each to operate with 15 watts power.

Such communication will be limited to the railroad classification yard. The messages to be transmitted will consist of orders relative to the classifying and sorting process in moving freight. The authorizations are for experimental purposes only. If the demonstration is successful, applications for operation on a permanent basis will be received from railroads interested in such service.

Though the Commission has granted experimental authorizations to certain railroads for the purpose of investigating the practicability of train radio communication, no permanent assignments of frequencies have been asked. An engineering conference was held by the Commission in 1936 for the purpose of allowing all interested parties to state their future radio needs. The evidence presented at this hearing was used as a basis for allocating frequencies of from 30,000 to 300,000 kilocycles. The railroad companies failed to appear or to make showing at that time as to the need for frequency assignments within that range for railroad use.

**Ralph Modjeski,** long-time recognized leader of the bridge-engineering profession in America died at the age of 79 in Los Angeles, Calif., June 26, following a long illness. Born in Poland and educated in Paris, he collaborated in 1885 on the construction of the Union Pacific Railroad bridge over the Missouri River at Omaha, Nebr. By 1893 he had opened consulting offices in Chicago. His famous structures include the Quebec cantilever bridge, the Philadelphia-Camden suspension bridge, and the San Francisco-Oakland Bay bridge, although his early fame was built on the construction of a series of notable simple-span railroad bridges across the Mississippi, including the Thebes and Memphis structures.

**Raymond F. Walter,** chief engineer of the United States Bureau of Reclamation since 1925, died in Fresno, Calif., June 30. Affiliated with the Reclamation service since 1903, he is credited with the direction of the planning and construction of all the great works for which recent Reclamation construction is notable, including Owyhee and Boulder Dams, the All-American Canal, the Grand Coulee project on the Columbia River, and the current Central Valley projects on the Sacramento River in California.

**Sidney O. Harper** has been appointed chief engineer of the United States Bureau of Reclamation, with headquarters at Denver, Colo. Since his graduation from the University of Colorado in 1907, he has spent his entire professional life with the Bureau. He became general superintendent of all reclamation construction in 1925, and his title was changed in 1930 to assistant chief engineer.

**Navigation Light on Memorial.** A navigation light, said to be the largest on the Great Lakes, and consisting of two 300-millimeter electric lanterns, each equipped with a 500-watt lamp and doublet lenses, recently has been installed on top of the 352-foot Perry's Victory and International Peace Memorial monument at Put-In Bay, Ohio. The light will operate about nine months of the year, and is also expected to aid aviation.

**Time Factor in Defense Production.** Declaring that the most misunderstood aspect of American industry is the time factor of preparation for mass production, C. F. Kettering (A'04, F'14) vice-president in charge of research, General Motors Corporation, recently pointed out that reports of producing 1,000 airplanes a day for the United States defense program may lead to disappointment unless the people can be given a clearer understanding of how long it takes to get ready for mass production of machines. It takes more than a year to put out a new model automobile, he said, suggesting that more complex machines require still more time for preparation. Military authorities must decide what type of defense equipment is needed; then American industry stands ready to produce it in quantity, Doctor Kettering declared. He warned that indecision or minor changes in specifications can effectively nullify a mass-production program.

**Coffin Award to Washington Water Power Company.** "For distinguished contribution to the development of electric power for the convenience of the public and the benefit of the industry," the Washington Water Power Company, Spokane, has been awarded the 1939 Charles A. Coffin gold medal, and related purse of $1,000 for the company's employment benefit fund. The award, which was established in 1922 by the General Electric Company as a tribute to the memory of its late founder Charles A. Coffin, was presented during the recent (June 3–6) annual convention of the Edison Electric Institute at Atlantic City, N. J.

# Education • • •

**Test Car to Purdue Museum.** The "Louisiana," historic interurban test car used in making air-resistance measurements at the Louisiana Purchase Exposition, St. Louis, Mo., in 1904, has been placed in the Railway Museum of Purdue University, Lafayette, Ind. At the close of the Exposition, the car was placed at Purdue by the Electric Railway Test Commission, and the University co-operated with the Commission in making further tests. Since 1910 the car has been part of the laboratory equipment for classes in electrical engineering, but removal of tracks by the local traction company caused its retirement to the museum.

**Iowa State Awards Medal.** The Marston Medal, highest honor of the engineering division of Iowa State College, Ames, was awarded this year to James W. Hook, president and director of the Geometric Tool Company and of the United Illuminating Company, New Haven, Conn., who was graduated in mechanical engineering from Iowa State in 1905.

**George Westinghouse Scholarships Awarded.** Ten high-school graduates have been selected to receive $3,000 George Westinghouse Scholarships for study at Carnegie Institute of Technology. The scholarship-holders will combine a formal engineering course with practical experience at Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. Ten similar scholarships were awarded in 1938 and in 1939. The 1940 winners are:

Aubrey Brister, Dallas, Tex.; W. Carpenter, Chattanooga, Tenn.; J. H. Dickson, Jr., Edgewood, Pa.; K. J. Ferrell, Washington, Pa.; L. S. Frost, Wilkinsburg, Pa.; W. D. Lyon, Fullerton, Calif.; Harold Schweinler, Jr., Tacoma, Wash.; B. L. Tennyson, West Orange, N. J.; J. A. Voelz, Shorewood, Wis.; J. L. Wolff, Greensburg, Pa.

# Other Societies •

## ASTM Announces Officers, Medalists

Officers for the American Society for Testing Materials for 1940–41, announced at the annual meeting of the society, Atlantic City, N. J., June 24–28, are as follows:

*President:* W. M. Barr, chief chemical and metallurgical engineer, Union Pacific Railroad Company, Omaha, Nebr.

*Vice-President:* H. J. Ball, head of the department of textile engineering, Lowell Textile Institute, Lowell, Mass.

*Members of executive committee:* R. C. Griffin, treasurer, Arthur D. Little, Inc., Cambridge, Mass.; P. D. Merica, vice-president and director, International Nickel Company, Inc., New York, N. Y.; Jerome Strauss, vice-president, Vanadium Corporation of America, New York, N. Y.; Stanton Walker, director, engineering and research division, National Sand and Gravel Association, Washington, D. C.; C. H. Fellows, head of chemical division, research department, Detroit Edison Company, Detroit, Mich.

The Charles B. Dudley Medal, for the paper of outstanding merit, constituting an original contribution to research, presented at the previous annual meeting of the society, was awarded to T. F. Willis and M. E. DeReus, Missouri State Highway Department, for their paper "Thermal Volume Changes and Elasticity of Aggregates and Their Effect on Concrete." The authors also received the first Sanford E. Thompson award, established by the society's committee on concrete and concrete aggregates for the outstanding paper in that field.

## *Future Meetings of Other Societies*

**American Chemical Society.** Fall meeting, September 9–13, 1940, Detroit, Mich.

**American Gas Association.** October 7–10, 1940, Atlantic City, N. J.

**American Institute of Mining and Metallurgical Engineers.** Regional meeting, September 10–13, Salt Lake City, Utah.

Joint meeting, AIME Coal Division, ASME Fuels Division, November 7–9, 1940, Birmingham, Ala.

**American Institute of Physics.** Conference on applied nuclear physics, with Massachusetts Institute of Technology, October 28–November 2, 1940, Cambridge, Mass.

**American Physical Society.** 237th meeting, November 22–23, 1940, Chicago, Ill.

**American Society of Civil Engineers.** Fall meeting, October 16–18, 1940, Cincinnati, Ohio.

**American Society of Mechanical Engineers.** Fall meeting, September 3–6, 1940, Spokane, Wash.

**American Transit Association.** 59th annual convention, September 23–26, 1940, White Sulphur Springs, W. Va.

**American Welding Society.** Annual meeting, October 20–25, 1940, Cleveland, Ohio.

**Association of Iron and Steel Engineers.** Annual convention, September 24–27, 1940, Chicago, Ill.

**Conference on Electrical Insulation (National Research Council).** October 31–November 2, 1940, Washington, D. C.

**Engineers' Council for Professional Development.** Annual meeting, October 24, 1940, Pittsburgh, Pa.

**Illuminating Engineering Society.** 34th annual convention, September 9–12, 1940, Spring Lake, N. J.

**National Electrical Manufacturers Association.** Annual meeting, October 27–November 1, 1940, New York, N. Y.

**National Metal Congress.** October 20–25, 1940, Cleveland, Ohio.

**National Safety Council.** October 7–11, 1940, Chicago, Ill.

# From AEC • •

ITEMS appearing under this heading are from the news service of American Engineering Council.

## Defense Program Begins to Take Form

Preparedness for war continues to occupy the center of the Washington stage, as the newly appointed National Defense Commission, still in the throes of organization, begins its tremendous task. As of July 1, appropriations already approved totaled $5,362,319,748, with additional amounts still to be acted upon by Congress.

The authorized strength of the Army has been increased from 227,000 enlisted men to 375,000 with clear indications that this number will soon be increased further, and Army officials protesting that 500,000 is the maximum number that can be trained in the immediate future because of limitations in officers and equipment. Nevertheless, a supplementary proposal will soon be submitted to Congress calling for the ultimate expenditure of between five and seven billion dollars, including large amounts for the procurement of tanks, anti-tank and anti-aircraft guns, other artillery, and motor vehicles, as well as perhaps $1,000,000,000 for government-owned plants to produce ordnance, chemicals, explosives, and other needed supplies.

One minor item in the program already approved is the voting of $18,500,000 for construction work in expanding 25 existing Army posts to provide training facilities for the expanded personnel.

As regards the Navy, Congress on June 27 voted funds for the construction of 68 new vessels and the modernization of 71 others now obsolete. Contracts covering some of the new construction were awarded within a few days, over $150,000,000 worth being assigned to five navy yards and an additional $500,000,000 to private shipyards. The former include 10 destroyers and 9 submarines; the latter 11 cruisers, 20 destroyers, 13 submarines, and 1 large seaplane tender. Additional awards will follow shortly. These contracts are in addition to those let earlier covering 23 vessels costing $350,000,000.

These figures are dwarfed, however, by a proposal already passed by the House providing for a two-ocean Navy increased 70 per cent in size over that now existing, and in-

volving a seven-year program to bring Naval strength to 750 vessels. If adopted, this program, in conjunction with construction already approved, will mean the expenditure of $1,000,000,000 per year for seven years.

To meet these demands the United States has, according to testimony by Rear-Admiral S. M. Robinson, chief of the Bureau of Engineering, a total of 137 privately owned shipways now in commission, plus 78 now out of service and 18 more in government-owned navy yards.

### SUPERVISION OF PROGRAM

To co-ordinate this tremendous effort the National Defense Commission is rapidly perfecting its organization, and the federal departments concerned are steadily increasing personnel. The Commission has named a large number of advisory committees representing various sectors of industry, and has placed Donald M. Nelson, head of the Treasury's procurement division, in charge of co-ordinating all purchases. Mr. Nelson, formerly with Sears, Roebuck & Company, will shortly recommend steps to simplify the government's cumbersome purchasing system and to procure priority for defense orders over private purchases when necessary. He will not take over the burden of direct purchases by the Army and Navy, but will co-ordinate them with those of other federal departments.

President Roosevelt has filled two of the three vacant executive White House posts granted by the Reorganization Act. These appointees will probably work closely with the defense commission. They are James V. Forrestal, president of Dillon, Read and Company, New York investment house, and Daniel J. Tobin, president of the Brotherhood of Teamsters and a vice-president of the American Federation of Labor.

Also tied in with the defense program are the appointments of Henry L. Stimson as Secretary of War and Frank Knox as Secretary of the Navy. The objective of these two appointments is to place the defense program on a nonpartisan basis.

### METHOD OF FINANCING

To defray part of the cost of the huge armament program Congress has enacted a new tax bill designed to yield an additional $1,000,000,000 annually in Federal revenues through increases in the income tax and in numerous other taxes, and has also increased the Federal debt limit from $45,000,000,000 to $49,000,000,000. President Roosevelt has also recommended the enactment of excess profit taxes, a suggestion now being considered by Congress.

To finance the large amount of plant expansion necessary to fulfill orders for armament the defense committee has already been voted $200,000,000, and the Reconstruction Finance Corporation has been given authority to make loans for the expansion of plant facilities and for the acquisition of materials needed for defense. As already stated, plans are rumored for the later request for an additional $1,000,000,000 for new plant construction under government auspices. War Department plans for the contingency of a major war estimate the need for 120 plants for the manufacture of special types of equipment and material, such as explosives and chemicals, that cannot readily be manufactured in existing factories.

### LABOR PROBLEMS

Employment in new fields for thousands of men and women naturally gives rise to many problems of adjustment that are being given careful consideration. Sidney Hillman, a member of the National Defense Committee, is in charge of this particular activity, and has already announced a plan to train 50,000 persons during the summer for industrial jobs connected with defense. State and industrial vocational training directors have met in Washington to discuss plans for this effort, which is expected to utilize all available facilities for apprentice training. Engineering schools will be called upon to give short courses in drafting, surveying, and other applicable techniques. The training will be financed by allotments from funds of the WPA and the Office of Education, supplemented by additional appropriations.

Looking beyond the immediate need, President Roosevelt has under study a plan for the annual training of 2,000,000 youths each year for national service in the armed forces, the service of supply, and the industries which support them. Details are unsettled.

The United States Employment Service is planning to expand its present set-up in order to take over the task of filling demands for both skilled and unskilled labor, if necessary by transfer from one region of the country to another. It requests all employers having present or potential need for such employees to inform it promptly of the extent and nature of these requirements.

Complicating the labor problem is the concurrent need of building up the enlisted strength of the Army and Navy. The Army plans this summer to call 9,000 reserve officers for special training, while the Navy has announced a plan to train 5,000 new ensigns by means of a special short course involving 90 days of shore training plus 30 days at sea.

### OTHER FEATURES

Among other activities of particular interest to engineers, are the following:

The Treasury has been voted $47,500,000 for the acquisition of strategic materials and minerals in which shortages are apt to develop. The Reconstruction Finance Corporation, as already noted, has also been authorized to make loans for a similar purpose, and has announced its intention of immediately purchasing 150,000 tons of rubber and 75,000 tons of tin to be held in reserve.

A third set of locks for the Panama Canal has been voted, with an appropriation of $15,000,000 plus $99,000,000 in contract authorizations.

President Roosevelt has asked for the appropriation of $25,000,000 for the installation of additional generating facilities in the Tennessee Valley Authority system.

The Commissioner of Patents has been authorized to withhold the granting, and hence the publication, of patents on devices relating to national defense.

The Census Bureau will give priority to the production statistics useful in defense in analyzing returns from the 1940 census.

Plans for the utilization of existing methods of communication for military purposes in case of war, and for the suppression of "fifth column" activities by radio amateurs, are being prepared by the Federal Communications Commission.

A National Defense Research Committee, headed by Dr. Vannevar Bush (A'15, F'24) president of the Carnegie Institution, has been organized "to accelerate the creation or improvement of instrumentalities for national defense." One of its problems will be the question of publishing the results of scientific investigations that might react to the advantage of a potential enemy.

## D. C. Jackson Heads Committee on Engineering Ethics

A committee has been appointed by President Alonzo J. Hammond of AEC to prepare a code of ethics for the engineering profession, which can be adopted by AEC member organizations with whatever modifications their specific needs require. Chairman of the committee is Dugald C. Jackson (A'87, F'12) professor emeritus, Massachusetts Institute of Technology, who represents the AIEE and the American Institute of Consulting Engineers. Other members are W. H. Kenerson, chairman, division of engineering, Brown University, representing the American Society of Mechanical Engineers; A. W. Dean, retired chief engineer, Massachusetts State Planning Board, American Society of Civil Engineers; J. W. Barker (M'26, F'30) dean of engineering, Columbia University, Society for the Promotion of Engineering Education. The American Institute of Mining and Metallurgical Engineers is being represented by Doctor Scott Turner as an observer.

In 1912 the AIEE board of directors formally adopted a "code of principles of professional conduct" for its members. Doctor Jackson served on the advisory committee that formulated the code, and since 1938 has been chairman of the Institute's standing committee on code of principles of professional conduct.

## Board to Co-ordinate Public Works Plans

President Roosevelt has directed Federal agencies engaged in construction activities to submit their plans for the future to the National Resources Planning Board, which will assemble them into a continuing plan looking six years into the future in order to indicate desirable priorities and avert conflicts among agencies engaged in different types of work.

The Board will maintain a review staff to work in collaboration with the director of the budget in the preparation of Federal programs affecting land (including reclamation, land purchases, forests, and parks); water (including flood control, power development, pollution); transportation (public roads, navigation improvements), and other undertakings involving Federal construction activities. It is expected to submit statements of plans and policies for transmission to Congress each year in connection with the annual budget that will permit the adjustment of Federal work to help stabilize trends in employment and business activity. To fulfill this duty it will also be necessary for the Board to assemble reports by its own staff and other Federal agencies reflecting such trends in economic conditions.

## Rates Based on Net Cost Set for Hydroelectric Plant

Acting on its first rate case involving a licensed hydroelectric development, the Federal Power Commission has ordered the Safe Harbor Water Power Corporation of Pennsylvania, to reduce its wholesale power rates so as to provide a net return of not more than 6 per cent on the net investment in its properties, plus adequate working capital, thus upsetting the traditional "fair value" rate base that gives weight, among other things, to estimated reproduction cost. The decision was supported by four of the five commissioners, with the dissenter differing, not in principle, but in the belief that a return of only $5^1/_2$ per cent should be permitted on the net investment.

In announcing its decision the Commission points out that the old rate-making principle has been time-consuming, burdensome, and subject to economic shocks. The net investment base, on the other hand, is founded upon established facts "and is not subject to the vagaries of theories, imagination, and abrupt fluctuations of prices and conditions."

The Safe Harbor Company is a wholly owned subsidiary of the Consolidated Gas, Electric Light and Power Company of Baltimore, Md., and the Pennsylvania Water and Power Company, which purchase its entire output.

## Tighter Federal Fiscal Control Urged

In a report published July 1, the Brookings Institution, an independent research group, makes a number of recommendations designed to increase the responsibility of Congress for Federal expenditures. Perhaps the most important of these is a proposal that the two houses create a joint committee on appropriations with a permanent staff of experts competent to advise on budgetary and financial matters, thus eliminating the present method of compromise adjustments of appropriations between actions taken by the House and the Senate, each advised by a separate committee on appropriations. The recommended procedure is already followed in matters of taxation.

Other recommendations include the reconstruction of the government's accounting and reporting system, and the elimination of political appointees from the Bureau of Internal Revenue and the Customs Bureau.

## New Air Routes Opened

Overseas air-transport service under American ownership and operation is being greatly expanded by Pan-American Airways' inauguration of new routes to Alaska and New Zealand, and increased service to South America.

Service to Alaska started June 24 with a flight from Seattle to Ketchikan, which continued next day to Juneau, where connections are made with existing airways serving many parts of the territory. Two round trips per week are scheduled.

Air-mail service was scheduled to open July 12 to New Zealand from San Francisco and Los Angeles in $4^1/_2$ days, with stops at Honolulu, Canton Island, and Noumea. Passengers will not be carried at present.

Service to South America has been augmented by daily trips from Miami to Buenos Aires, alternating between the east- and west-coast routes, in addition to four new schedules in the Caribbean area and a fifth through Central America and across the northern part of South America. Four-engined Boeing "strato-clippers" will operate twice weekly at high altitudes between Miami and Barranquilla, Colombia, where connections will be made for points further south.

New development in continental air service is the strato-liner service from New York, N. Y., to the Pacific Coast, which started July 8, 1940.

# Letters to the Editor • • •

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy as inked drawing without lettering, the other lettered. Captions should be supplied for all illustrations.

## Matrices and Dyadics

*To the Editor:*

It is very gratifying to note that in spite of the wars there are still persons interested in matrices and dyadics as shown by papers by Reed[2] and by Pipes.[1,3] After reading these more recent contributions on the subject, the writer is still of the opinion that in the application of matrices and dyadics to the analysis of *three-phase circuits*, dyadics have many valuable properties not shared by matrices.

Take Reed's paper.[2] He has used the following matrices:

$$\mathbf{H}_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \mathbf{H}_2 = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix},$$

$$\mathbf{H}_3 = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}, \text{ and } \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$$

in addition to relations for the transformation of line-to-line quantities to line-to-neutral quantities and vice versa. It will be noted that $\mathbf{H}_1$, $\mathbf{H}_2$, $\mathbf{H}_3$ are exactly the writer's[4] $\mathbf{I}$, $\mathbf{K}$, $\mathbf{J}$, the properties of which have been discussed at some length. As for the last matrix, it is nothing more than three times the dyadic $(\mathbf{I}-\mathbf{uu})$, known as the "zero-sequence eliminator". In this dyadic **u** is the versatile isoclinic unit vector, that is, a vector equally inclined to the three rectangular co-ordinate axes, which plays a rôle in star-delta transformations much like that played by the imaginary unit $j=\sqrt{-1}$ in single-phase discussions of balanced three-phase circuits. Just look at the transformation formulas (reference 4, page 46).

$$\mathbf{E}_{bc} \text{ (line-to-line)} = \sqrt{3}\mathbf{u}\times\mathbf{E}_a \text{ (line-to-neutral)},$$

$$\mathbf{I}_a \text{ (star value)} = -\sqrt{3}\mathbf{u}\times\mathbf{I}_{bc} \text{ (delta value)}$$

and compare them with:

$$\mathbf{E}_{bc} = \sqrt{3}j\mathbf{E}_a \text{ and } \mathbf{I}_a = -\sqrt{3}j\mathbf{I}_{bc}$$

The writer heartily endorses Reed's statements, made in discussing Pipes' recent paper[3]:

"... insofar as static networks are concerned, the tensor concept and, therefore, transformation from an old to a new space is not necessary. In fact, the *C* matrix of Kron and the *A* matrix of Pipes are somewhat artificial when applied to static network theory. These transformations are used to establish the impedance matrix for the physical network. But this may be done rather easily by means of Kirchhoff's voltage equations in terms of Maxwell's cyclic currents ..."

The dyadician's viewpoint in the analysis of such circuits is best illustrated by using the wye-wye circuit of Pipes. After several transformations, during the course of which a good number of zeros were introduced in order to construct high-order matrices out of low-order ones, Pipes[3] eventually calls attention to his equation 45. This equation holds the key to the solution of the present problem and can be set up without any ado by the dyadician from the single-line diagram of the wye-wye connection thus:

$$\mathbf{E}_s = \mathbf{E}_r + (\mathbf{Z}_s + \mathbf{Z}_L + \mathbf{Z}_r)\cdot\mathbf{I}_n$$

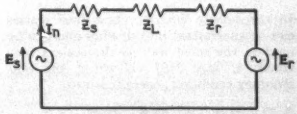



Figure 1

As for the delta-delta and delta-star networks, the reader interested in the viewpoint of the dyadician will find a good many solved examples in chapter 5 of reference 4.

Aside from the remark of Reed concerning static networks already quoted, the writer would like to go one step farther and state that even in *three-phase machines* (whether operated normally or non-three-phase), the useful and usable reference axes are limited in number (reference 4, chapters 7 and 8). These are:

1. The phase axes, i, j, k;
2. The stationary compler axes of symmetrical components, u, f, b;
3. The rotating axes, u, s, n; and
4. The axes of two-reaction theory, u, d, q.

The transformation from any one system of the above to any other is not so difficult as to require a *general* transformation theory for its understanding. It seems that the utility of the general transformation is not at all realized in the considerations involving *three-phase circuits*, whether static or rotating.

Be he a dyadician or a matrician or a tensorist, his avowed object is generalization. It is the opinion of the writer that in

engineering applications, generalizations should be along directions which will make the new relations more readily understood from simple analogy with the old and well-established ones. Thus the generalization of Ohm's law from $E = RI$ for a d-c circuit to $\mathbf{E} = \mathbf{Z}\mathbf{I}$ for an a-c circuit and to $\mathbf{E} = \mathbf{Z} \cdot \mathbf{I}$ for a three-phase circuit deserves high commendation. It is in conformity with this basic principle when a dyadician analyzes a three-phase network after the pattern used in the study of single-phase circuits. The combination of partitionable dyadics, or square matrices having nine elements, into rectangular or square arrays with lots of added zeros naturally is not in keeping with the purpose of the dyadician. To the writer and other children playing with mathematical tools, such a "building" program as that given by Pipes looks more like the work of a skillful magician (matricians, please pardon) whose trick is difficult to expose, than like that of a careful, perhaps conservative dietitian (dyadician) whose prescription is easy to follow.

While on the subject of generalization, an interesting example immediately seen by the dyadician but not yet brought to light by the matrician so far is that of general circuit constants $A, B, C, D$. These four scalars appear in the following equations relating to the sending- and the receiving-end quantities:

$$E_s = AE_r + BI_r$$
$$I_s = CE_r + DI_r$$

and they satisfy the constraining condition imposed by a bilateral network:

$$AD - BC = 1$$

In three-phase circuits, these four scalars can be generalized into dyadics and can be used in the same way as the scalars (reference 4, page 248). However, the constraining condition generalizes into

$$\mathbf{A} \cdot \mathbf{D}_t - \mathbf{B} \cdot \mathbf{C}_t - \mathbf{I} - \mathbf{D} \cdot \mathbf{A}_t - \mathbf{C} \cdot \mathbf{B}_t$$

in which the subscript $t$ is used to denote the transposed dyadic. It is quite apparent why a matrician missed this generalization, because his creed is to build from low-order matrices high-order arrays.

In concluding, an apology for constantly referring to the book "Dyadic Circuit Analysis" is certainly in order, lest the reader may think this an advertisement. The fact is that the writer's personal collection of papers on dyadics have all been lost in Peiping when Japanese soldiers took over the campus of National Tsing Hua University in 1937. Herein lies an irony of fate, for the first paper on dyadics was written in response to the call of the Japanese Government when they convened the World's Engineering Congress at Tokyo in 1929 and the final manuscript on the same subject barely escaped the ire and the fire of the army from the same government. Well, a cat often devours what she begets! Why complain?


REFERENCES

1. Matrices in Engineering, L. A. Pipes. Electrical Engineering (AIEE Transactions) volume 56, September 1937, pages 1177–90.

2. The Properties of Three-Phase Systems Deduced With the Aid of Matrices, M. B. Reed. AIEE Transactions, volume 57, 1938 (February section), pages 74–7.

3. Transformation Theory of General Polyphase Networks, L. A. Pipes. AIEE Transactions, volume 59, 1940 (February section), pages 123–8.

4. Dyadic Circuit Analysis (a book), A. Pen-Tung Sah. International Textbook Company, Scranton, Pa., 1939.



A. Pen-Tung Sah (A'35, M'36)

(President, National University of Amoy, Changting, China)


## Nonexistent Difficulties in Welding

*To the Editor:*

Arc welding has too many doctors. An operation which is perfectly natural, very simple, and very easily accomplished largely has been changed in the minds of the public to an art which takes on the mystery of voodooism with an admixture of the art of the medicine man.

The public is beginning to think that the welding operator is a cross between a miracle man and a professional magician. This opinion is groundless. The only thing that a welding operator can do is to hold the end of an electrode at a certain distance above the deposited metal and advance it at a certain speed along the seam to be welded. There is nothing more involved in the operation. It is neither complicated nor difficult. As a matter of fact, with proper electrode, proper setting of the welding machine, and proper preparation of the work, it is practically impossible to make a weld which will not stand up in service without having its defects so evident to the inspector that he would immediately reject it. It is possible to have defects in the steel that cannot be seen, which will make a steel structure dangerous. It is impossible, however, to make a weld on that structure which is dangerous without its being obvious to anyone looking at the weld.

The chief reason we hear so much about the necessity of skill and care in welding is that the operation itself is so simple that it is difficult to find much about it to discuss in papers, lectures, and statements. Therefore, many of the eccentricities which are volubly discussed consist of theoretical possibilities that usually exist only in the minds of the lecturers and seldom exist in reality.

It is time that we got away from trying to make this very simple operation mysterious. It is time we recognize the fact that the metal deposited by the shielded-arc electrode is definitely better than the parent metal it is joining. It is time we recognize that there has never been a failure on an insured pressure vessel made by the shielded-arc process. It is time we recognize that in the usual design if only half a weld is made it will withstand all of the normal requirements of the structure. It is time we recognize that failures never exist in welds which are made by the methods recommended by any reliable manufacturer. It is time we recognize that there is no mystery in welding, and that making a welded joint is far more simple than making a riveted joint and more simple than making the steel which is joined together by this process. It is time we recognize that to spend time, money, and attention in removing the least possible flaw from the deposited metal is silly in the light of the obvious flaws which must occur in the parent metal. A factor of safety is used to guard against these flaws. That is more than is needed in any commercial weld.

When we do recognize these facts we will have done two things: First, we will have given the green light to one of the most economical processes now known for the production of many structures; secondly, we will have removed one of the fears which the uninitiated have developed regarding a perfectly normal manufacturing operation.


J. F. Lincoln (A'08, F'39)

(President, Lincoln Electric Company, Cleveland, Ohio)


# Books Received

**The following new books** are among those recently received at the Engineering Societies Library. Unless otherwise specified, books listed have been presented by the publishers. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books in question.

DESIGN OF ELECTRICAL APPARATUS. By J. H. Kuhlmann. Second edition. John Wiley and Sons, New York, 1940. 506 pages, illustrated, 9½ by 6 inches, cloth, $5.00. Practical methods of design are given for the d-c machine, synchronous machine, induction motor, and transformer. Includes complete explanations of the construction, procedure, formulas and limits of design, and sample calculations for several pieces of electrical apparatus.

ECONOMICS OF TRANSPORTATION IN AMERICA. By E. T. Healy. Ronald Press Company, New York, 1940. 575 pages, maps, etc., 9½ by 6 inches, cloth, $4.00. A study of economic forces and motives, and the reasons for economic phenomena in transportation. A historical introduction is followed by an analysis of demands for transportation and a résumé of the construction and development of transportation facilities. The functioning of these facilities and their regulation by government action are considered in detail. Brief bibliography and list of railroad histories.

PLASTICS IN ENGINEERING. (Machine Design Series.) By J. Delmonte. Penton Publishing Company, Cleveland, Ohio, 1940. 616 pages, illustrated, 9½ by 6 inches, cloth, $7.50. Intended as a reference work for the machine designer and manufacturer, rather than the chemist. Reviews the various types of plastics, methods of compounding, and physical and chemical properties, and discusses methods of molding, uses for bearings, gears, and other machine parts, engineering applications of plastics, fabrication and finishing of plastic parts, common failures, etc. A chapter is devoted to synthetic rubbers.

PROCEDURE HANDBOOK OF ARC-WELDING DESIGN AND PRACTICE. Sixth edition. 1940. Lincoln Electric Company, Cleveland, Ohio, 1940. 1,117 pages, illustrated, 9 by 6 inches, cloth, $1.50 in United States; $2.00 elsewhere. Intended as a reference book on arc welding. The various forms of arc welding are described, welding of various metals explained, and designing of machinery and structures for arc-welded construction discussed. New edition brought up to date and expanded.

PRINCIPLES OF ALTERNATING-CURRENT MACHINERY. (Electrical Engineering Texts.) By R. R. Lawrence. Third edition. McGraw-Hill Book Company, New York, 1940. 678 pages, illustrated, 9 by 6 inches, cloth, $5.50. The principles underlying the construction and operation of the more important types of a-c machinery are treated under eight headings: synchronous alternators, static transformers, synchronous motors, parallel operation of alternators, synchronous converters, polyphase induction motors, single-phase induction motors, and series and repulsion motors. Revised with new material added.

PRINCIPLES OF DIRECT-CURRENT MACHINES. (Electrical Engineering Texts.) By A. S. Langsdorf. Fifth edition. McGraw-Hill Book Company, New York, 1940. 746 pages, illustrated, 9½ by 6 inches, cloth, $5.50. Aims to supply a reasonably complete treatment of the fundamental principles that underlie the design and operation of all types of d-c machinery. In addition to the customary revision to bring the material up to date, the present edition includes a more extensive treatment of the general principles of electricity and magnetism, and new sets of problems.

# Institute Activities

## Institute Publication Procedure Modified to Improve Service

ALTHOUGH the general reaction of the Institute's membership to the present publication policy has been very favorable, operating experience under this policy has indicated that still better publication service could be provided with no net increase in publication expense if certain minor modifications were made.

The two principal adverse criticisms of the present policy are that too many technical program papers are omitted from ELECTRICAL ENGINEERING and that there is too long a delay between presentation of technical program papers and their publication. Also there has been brought to the attention of the publication committee the desire to have abstracts of technical program papers and conference presentations published in advance of conventions and District meetings.

To provide these improvements without involving a net increase in publication expense, the publication committee worked up a set of proposals and these were approved by that committee at its meeting on May 10, 1940. These proposals then were submitted through the chairman of the technical program committee to all members of that committee and to the several hundred members of the Institute's various technical committees. A letter ballot showed a substantial majority in favor of all proposals. Then, at the annual conference of officers, delegates, and members held during the recent summer convention in Swampscott, these same proposals were considered and individually approved either unanimously or by a large majority. Finally the proposals were submitted to and approved by the board of directors at its June 27 convention meeting.

The proposals, which appear in full at the end of this article, provide the following improvements:

1. The publication in ELECTRICAL ENGINEERING of a larger number of technical program papers.

2. A substantial reduction in the time between the presentation of technical program papers and their publication. For example, publication of winter convention papers will begin in January, instead of in May or June.

3. Much earlier publication of the discussions of most of the technical program papers.

4. Advance publication of abstracts of technical papers.

5. Assurance to authors of technical papers approved by the technical program committee and presented at national or District meetings that the papers will be published in ELECTRICAL ENGINEERING if kept within a limit of six printed pages.

6. Increased readability of technical program papers appearing in ELECTRICAL ENGINEERING, secured by encouraging authors to be brief.

7. More orderly and convenient form for the annual bound volumes of TRANSACTIONS. (By the close of the necessary transition period, the annual volume will contain all technical program papers and approved discussion presented during the corresponding calendar year.)

The present modifications involve no change in the following principal features of the publication policy which has been in effect for the last several years.

1. The publication of a substantial number of high-quality general-interest articles in each issue of ELECTRICAL ENGINEERING.

2. TRANSACTIONS a complete repository for all technical papers reviewed and approved for presentation by the technical program committee.

3. Provision of advance pamphlet copies of authors' manuscripts of all technical papers reviewed and approved for presentation by the technical program committee.

4. Provision of the "Transactions Supplement" to ELECTRICAL ENGINEERING, which contains all papers and discussions published in the annual bound volume of TRANSACTIONS which have not been published in the TRANSACTIONS sections of ELECTRICAL ENGINEERING.

Plans are under way in the editorial office to make these modifications as promptly as possible because unless an immediate start is made, the transition cannot be completed in time to have the 1942 bound volume of TRANSACTIONS appear in the more orderly and convenient form.

It is and has been the aim of the publication committee to give Institute members the kind of publication service which they want within the limits set by the AIEE constitution and bylaws, by a high standard of quality, and by a limited publication budget. The comments and criticisms of Institute publications that have been submitted by individual members have been very helpful to the publication committee and to the editor in effecting this aim. Member comments and criticisms of the modifications just adopted will be very welcome. These should be sent either to the editor or to the chairman of the publication committee.

### TEXT OF APPROVED PROPOSALS

**PROPOSAL A: Provide for early publication of abstracts of approved technical program papers, for publication of approved abstracts of unapproved technical program papers or presentations and for separate "abstract bulletin."**

*Explanation:* This is an extension of the present publication policy which now provides for the publication of authors' abstracts of approved technical program papers. The extension would comprise:

1. The immediate publication in ELECTRICAL ENGINEERING of the abstracts of approved papers separate from the papers themselves as soon as possible after the release of the manuscript for preparing "advance copies."

2. The publication of approved abstracts of unapproved papers or presentations such as (a) District meeting papers not reviewed and approved by the technical program committee and (b) informal conference presentations.

3. The publication of an "abstract bulletin" to be mailed with convention or meeting programs to include abstracts released too late to get in ELECTRICAL ENGINEERING in advance of the convention or meeting but in time to be mailed with the program.

**PROPOSAL B: Limit advance pamphlet copies of authors' manuscripts to those reviewed and approved by the technical program committee.**

*Explanation:* This is merely a confirmation of the present publication policy put into effect at the time when the present form of advance pamphlet copies was adopted. The reasons back of this policy are:

1. The Institute should not publish under its name material that has not been properly reviewed and approved.

2. The Institute's limited publication budget should be conserved as far as possible for uses which benefit our whole membership rather than only very small groups. (Even with the increased prices proposed for advance pamphlet copies, they would not be nearly self-supporting.)

**PROPOSAL C: Reduce the net cost of providing advance pamphlet copies of authors' manuscripts reviewed and approved by the technical program committee by putting these on a more nearly self-supporting basis.**

*Explanation:* The cost of some of these pamphlet copies approximates 50 cents each, the bulk of them costing from 10 to 25 cents each (not including postage and handling). The following price schedule is proposed:

| Size of Pamphlet (Pages) | Price Per Copy At Registration Desk | Price Per Copy By Mail |
|---|---|---|
| 12 or less | $0.10 | $0.15 |
| 16 | .15 | .20 |
| 20 | .20 | .25 |
| 24 or more | .25 | .30 |

(This price schedule is not retroactive. It is expected to go into effect October 1, 1940.)

Even at these increased prices the net cost to the Institute would be several thousand dollars per year. While these pamphlet copies fill an expressed and important need, they serve a relatively small portion of our total membership and hence the cost to the general membership should be kept at a minimum. Additional income from the sale of these pamphlet copies would permit the publication of more material in ELECTRICAL ENGINEERING and TRANSACTIONS without increasing the total net publication expense.

**PROPOSAL D: Omit discussions from Electrical Engineering and publish these semiannually in two "Transactions Supplements."**

*Explanation:* This proposal has three objects:

1. To reduce substantially the time between presentation and publication. For instance, under the present arrangement, the publication of winter convention papers does not start until the May issue of ELECTRICAL ENGINEERING, while under the proposed arrangement publication would start with the January issue and be completed with the June issue; a gain of four months.

2. To provide for publishing more technical program papers in the TRANSACTIONS section of ELECTRICAL ENGINEERING. Discussions now require over 20 per cent of the pages. By omitting discussions, these pages could be used for additional papers without increase in publication expense.

3. To make the bound volumes of TRANSACTIONS more orderly and more convenient to use. For instance, with the proposed arrangement in effect, the bound volume of TRANSACTIONS, dated 1942, would contain all approved technical program papers presented in 1942. Under the present arrangement, each volume is a mixture in this respect.

The discussions of all winter convention papers would be published in the first semiannual issue of the "Transactions Supplement" which would come out in June of each year. While a small part of the winter convention discussions (that now appearing

in the May issue of ELECTRICAL ENGINEERING) would be delayed for one month, all discussions of winter convention papers would be published in June so that most of the discussions would be published considerably earlier than is the case under the present arrangement. Each paper having discussion would carry a footnote indicating in which issue of the "Transactions Supplement" the complete discussion could be found. The discussions for the whole year would appear all together in the corresponding bound volume of TRANSACTIONS.

**PROPOSAL E: Place page limit (six pages in type) on technical program papers to appear in the Transactions section of Electrical Engineering.**

*Explanation:* This proposal has two objects:

1. To provide for publishing more technical program papers in the TRANSACTIONS section of ELECTRICAL ENGINEERING without increasing publication expense.

2. To place directly within the control of the author the primary consideration on which the decision to publish or not to publish in ELECTRICAL ENGINEERING would be based.

Mere suggestions to authors to be brief have not produced the desired results even though in a great many cases brevity would increase the quality and value of papers. It is expected that the proposed procedure would be much more effective. It is not intended to omit all papers that exceed the limit, but rather to assure publication in ELECTRICAL ENGINEERING of all approved papers that do not exceed the page limit. With this and the other proposals in effect, many of the longer papers also would appear in ELECTRICAL ENGINEERING, but authors would know in advance that papers exceeding the page limit might not appear there.

For convenience to them, the limit would be stated to the authors in terms of number of words and the equivalent number of words for each column-inch of illustrations.

**PROPOSAL F: Remove restriction set by publication budget on the number of papers which may be approved by technical program committee.**

*Explanation:* There is in fact no such actual restriction at the present time because the publication budget has been made up to provide for the space that the technical program committee has estimated would be needed on the basis of the established publication policy. Also other limitations are present, viz., the number of papers that can be handled satisfactorily in one session, the number of parallel sessions that can be handled separately, and the availability of actual manuscripts of papers of sufficiently high quality, etc. There is, of course, a limit to the size of the budget which the publication committee can have approved by the board of directors because our total income is necessarily limited. However, the removal of the publication-budget restriction should clarify the situation and avoid any conflict, real or apparent, between the activities of the two committees. With the publication-budget restriction removed from the technical program committee schedules, only the publication committee activities would be restricted by the publication budget. That would seem to be the logical arrangement.

With this modification in effect there would be no change in the present technical program committee procedure which is as follows:

1. Review and approve or disapprove all technical papers submitted for program consideration.

2. Arrange desirable national convention programs using only approved papers which are considered suitable for presentation. Also furnish approved papers to the local committees arranging District meeting technical programs.

3. Deliver to publication committee all approved papers whether scheduled for presentation or not.

The procedure in the publication committee would not differ in any general way from the present one but the proportion of the total number of technical-program-committee-approved papers appearing in ELECTRICAL ENGINEERING would vary depending upon the available budget. However, with proposed changes *C*, *D*, and *E*, above, in effect, the number of such papers appearing in ELECTRICAL ENGINEERING would be increased without any increase in publication budget. Specifically publication committee procedure would be:

4. Publish in TRANSACTIONS all technical papers (and discussions of them) approved by Technical program committee.

5. Publish in TRANSACTIONS section of ELECTRICAL ENGINEERING without discussions as many technical papers approved by technical program committee as publication budget permits.

6. Publish in two semiannual issues of the "Transactions supplement" the discussions of all approved technical papers presented at national conventions or District meetings. Also publish in the "Transactions Supplement" those approved technical papers presented at national conventions and District meetings which are not published in the TRANSACTIONS section of ELECTRICAL ENGINEERING.

7. Provide pamphlet copies of all technical papers approved by technical program committee in accordance with price schedule under C above.

As a guide to the publication committee, the technical program committee would be asked, near the close of each appropriation year, to *estimate the number of papers* it would approve during the next appropriation year, but this estimate would place no restriction on the technical program committee as to the number of papers it actually would approve.

# Technical Program—Pacific Coast Convention

**Photo-offset copies of authors' manuscripts, except addresses, may be obtained as soon as available in advance of the convention by writing to the AIEE order department, 33 West 39th Street, New York, N. Y. Only numbered papers will be available in advance-copy form. If ordered by mail, price 10 cents per copy; if purchased at Institute headquarters or at the convention, 5 cents per copy. Mail orders (particularly from out-of-town members) are advisable, as an adequate supply of each paper at the meeting cannot be assured. Coupon books in $1 and $5 denominations are available for those who wish to avoid remittance by check or otherwise. Most of the papers ultimately will be published in ELECTRICAL ENGINEERING or the TRANSACTIONS.**

## Tuesday August 27

### 10:00 a.m. Opening Session

Address of welcome. N. B. Hinson, convention chairman

Address, "Science and Superstition." R. W. Sorensen, president, AIEE

Address. Douglas Shearer, sound director, Metro-Goldwyn-Mayer Studios

### 2:00 p.m. Protective Devices

40-127. AN IMPROVED A-C PILOT WIRE RELAY. **J. H. Neher**, Philadelphia Electric Company, and **A. J. McConnell**, General Electric Company

40-115. DISPLACEMENT AND DIFFUSION IN FLUID FLOW ARC EXTINCTION. **Joseph Slepian**, Westinghouse Electric and Manufacturing Company

40-114. THE VERTICAL FLOW INTERRUPTER AND ITS APPLICATION TO OIL-POOR CIRCUIT BREAKERS. **B. P. Baker**, Westinghouse Electric and Manufacturing Company

40-129. POSSIBILITIES AND METHODS OF EXTENDING A CARRIER-CURRENT RELAY CHANNEL TO OTHER USES. **R. M. Smith** and **S. L. Goldsborough**, Westinghouse Electric and Manufacturing Company

## Wednesday, August 28

### 9:00 a.m. Power Transmission and Distribution

40-133. SUPERPOSITION METHODS IN CALCULATING EFFECTS OF ADDITIONS TO POWER SYSTEMS. **V. G. Rettig**, Cincinnati Gas and Electric Company

40-126. CAPACITORS AND CIRCUIT PERFORMANCE. **J. W. Butler**, General Electric Company

40-107. SHIELDING OF TRANSMISSION LINES. **C. F. Wagner, G. D. McCann**, and **G. L. MacLane, Jr.**, Westinghouse Electric and Manufacturing Company

40-134. A DOUBLE-BREAK OIL- OR GAS-BLAST POWER FUSE. **G. Leslie Hill**, Pacific Gas and Electric Company

### 9:00 a.m. Conference on Governors, Frequency Control, Load Swings, etc.

### 2:00 p.m. Electrical Machinery

40-132. AN ELECTRICAL GOVERNOR. **Frank I. Morgan**, Pennsylvania Water and Power Company

40-130. POWER-FACTOR TESTING OF TRANSFORMER INSULATION. **J. B. Hodtum**, Allis-Chalmers Manufacturing Company

40-120. SOME ACCELERATION TESTS ON LARGE SYNCHRONOUS PUMP MOTORS. **R. W. Ager**, University of California

40-135. A GENERALIZED EQUIVALENT CIRCUIT IN THE THEORY OF POLYPHASE COMMUTATOR MOTORS. **W. B. Coulthard**, University of British Columbia

### 2:00 p.m. Instruments, Measurements, and Basic Sciences

40-108. TRANSIENT ANALYSIS OF COMPLETELY TRANSPOSED MULTICONDUCTOR TRANSMISSION LINES. **Louis A. Pipes**, Harvard University

40-128. BRAKING MAGNETS FOR WATT-HOUR METERS. **I. F. Kinnard** and **J. H. Goss**, General Electric Company

40-136. VARIO-LOSSER CIRCUITS. **W. R. Bennett** and **S. Doba**, Bell Telephone Laboratories

40-131. BEHAVIOR OF POINT GAPS AT 60 CYCLES. **Jean V. Lebacqz**, University of California.

### 2:00 p.m. Student Technical Session

PRIEST RIVER POWER DEVELOPMENT. **Albert Kassens**, University of Idaho

THE MEASUREMENT OF REACTIVE VOLT-AMPERES BY MEANS OF SYMMETRICAL COMPONENTS. **Charles B. Lee**, University of Washington

ELECTRICAL DETERMINATION OF WATER-FLOW CONTOURS. **Carl J. Bratfisch**, University of Southern California

A STUDY OF ARC-EXTINGUISHING PHENOMENA. **Don J. Nairn**, University of Southern California

CONSTRUCTION OF A 2,000,000-VOLT IMPULSE GENERATOR. **W. R. Johnson**, Stanford University

## Thursday, August 29

### 9:00 a.m. Communication—Joint Session With IRE

Address, "Frequency Modulation." Major E. H. Armstrong

Address. Speaker to be announced.

### 2:00 p.m. Student Technical Session

A ONE-METER REPLICA GRATING SPECTROGRAPH. **Joseph Mitch**, Montana State College

AN IMPROVED-TYPE LOSSER MODULATOR. **V. S. Carson**, Stanford University

A STABILIZED NEON-TUBE COUPLED AMPLIFIER. **W. H. Huggins**, Oregon State College

DESIGN OF A RADIO-FREQUENCY PHASE METER. **T. L. Wilson** and **C. R. Knight**, University of Utah

PERMEANCE OF TAPERED SLOTS IN ELECTRICAL MACHINES. **T. S. Wang**, California Institute of Technology

## Program Completed for Pacific Coast Convention

All is in readiness for the 1940 Pacific Coast convention to be held in Los Angeles, Calif., August 27–30. An attractive program of technical and recreational features, which leaves little to be desired, has been arranged by the committee. Southern California by virtue of its proximity to the mountains and the sea offers many vacation possibilities. Convention headquarters will be at the Ambassador Hotel, which has excellent facilities.

Information on the various features of the convention, technical sessions, student activities, entertainment, sports, inspection trips, registration and hotels, as well as a complete schedule of events, was given in ELECTRICAL ENGINEERING for July, pages 288–9. The technical program, comprising five technical sessions, a technical conference, and two student technical sessions, is presented on the preceding page.

# 56th Annual Summer Convention Held in Swampscott, Mass.

FOR the third time in Swampscott, and for the eighth time in New England, the Institute's summer convention was held at the New Ocean House, Swampscott, Mass., June 24–28 inclusive. Previous Swampscott conventions were held in 1923 and in 1929. Other AIEE summer conventions held in New England include Boston, Mass., 1890; Eliot, Me., 1897; Boston, Mass., 1899; Great Barrington, Mass., 1902; Boston, Mass., 1912.

Registered attendance this summer at Swampscott, as may be noted from the accompanying tabulation, totaled 1,014, substantially above the over-all average of 822 for the period 1920–39. Other details pertaining to the great variety of convention activities may be found on the following pages.

## Annual Business Meeting

In convening the Institute's official annual meeting at 10 o'clock Monday morning, June 24, in the ballroom of the New Ocean House, General Convention Chairman J. I. Hull gave voice to a convention theme:

"As I face this convention, I sense a conference of an outstanding part of the American engineering brotherhood. You are here to report progress, to confer, to preview, and to guide the future. Nobody assigned to you your roles as engineers, teachers, industrial practitioners. Through parental counsel or contact or study, you made your youthful comparisons, mapped your courses, and now you are actually living them. In following our calling as engineers, we partake of the bounty of America, of the bounty of abundant nature whose resources are ready to serve him who will rightly fashion and cleverly contrive; the bounty of abundant calling to be called to one's likings and abilities; of abundance of amiable people with whom to live and work in friendship and co-operation; the abundance of opportunity to make a contribution of usefulness to better America for ourselves and for the future."

Chairman Hull successively introduced the Honorable Frederick Cook, Secretary of State for the Commonwealth of Massachusetts, who spoke briefly on behalf of Governor Saltonstall; AIEE Vice-President C. L. Dawes of Harvard University, who elaborated on the points of scenic, technical, and historical interest to be found in the vicinity; and President F. Malcolm Farmer who presided for the business session. President Farmer gave special recognition to the effective work of the various convention committees.

### REPORTS OF THE BOARD OF DIRECTORS AND THE COMMITTEE OF TELLERS

An abstract of the annual report of the board of directors for the fiscal year ending April 30, 1940, was presented by National Secretary H. H. Henline in accordance with custom.

Although previously organized Sections so thoroughly covered the country that the early organization of new Sections seemed improbable, three new Sections were authorized and went into operation during the year: Charleston, W. Va.; El Paso, Texas; and the State of South Carolina. Also, one new Branch was formed, at the University of Alberta; this brings the present total to 70 Sections and 121 Student Branches. All Sections reported some activity during the year.

For the sixth consecutive year, the number of Section meetings reported increased, from a total of 635 the preceding year to a total of 701 for the year recently ended. In addition to District meetings and national conventions, there was a total of more than 2,000 Section and Branch meetings, with an average reported attendance of more than 78 per meeting. The Institute membership grew during the year from 16,605 to 17,213, some 6 per cent below the predepression level compared with 22 per cent for the depression low point.

Secretary Henline emphasized the fact that the annual report of the board of directors is presented to the membership each year in conformity with the constitutional requirements that the board shall report to the membership at the close of the fiscal year, April 30, upon the activities, the properties owned, the income, the expenditures, and all other essential facts bearing on the status of the Institute. He pointed out that this report actually is a series of many brief reports from the various responsible committees, that it contains information of interest and value to every member of the Institute, and that it had been distributed to the entire membership of the Institute through the medium of the July issue of ELECTRICAL ENGINEERING (pages 290–303 inclusive). Also, the few brief facts pertaining to Section and Branch activities are but a summation of the detailed information given on pages 250–3 inclusive of the June issue.

Upon presentation of the tellers' report by National Secretary Henline, President Farmer declared the new officers elected and charged with the responsibility of beginning their administrative term August 1, 1940. He officially inducted President-Elect Sorensen into office, and made the traditional presentation of the president's badge. For the substance of the tellers' report, and the list of new Institute officers, see page 289 of the July issue of ELECTRICAL ENGINEERING.

### TREASURER'S REPORT

Summarizing the detailed report contained in the report of the board of directors, Treasurer W. I. Slichter reported that Institute income for 1939–40 was some $292,914 as compared to some $280,144 for the preceding year; that Institute activities, and consequent expenses, had been increased in about the same proportion for the benefit of the membership at large. As to the capital reserve (emergency savings) fund, Treasurer Slichter reported that the present total reserves amount to some $240,494; that in terms of market value May 1, 1940, securities in hand have a cash value of more than 90 per cent of their book value, representing relatively a very favorable position.

### PRIZE AWARDS

Acting for Chairman J. W. Barker of the committee on award of Institute prizes, I. Melville Stein, a member of the committee, read a report covering the national awards made for technical papers presented during the calendar year 1939. The substance of this report was published on page 254 of the June 1940 issue of ELECTRICAL ENGINEERING; similarly, District prize paper awards were published in the July issue, pages 304–05.

On behalf of the committee, Mr. Stein called attention to the lack of papers of national prize caliber on the subject of public relations, and urged the development of more papers within the scope of that important subject. With reference to the subject of Student Branch papers, Mr. Stein emphasized that although there usually are enough for a satisfactory competition for the national prizes, it was the consensus of the committee that many good Student Branch papers are being written

**Analysis of Attendance at 1940 Summer Convention, Swampscott, Mass.**

| Classification | Districts | | | | | | | | | | Foreign | Totals |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | |
| Members | 280 | 110 | 127 | 25 | 62 | 4 | 20 | 10 | 8 | 7 | 1 | 654 |
| Men guests | 57 | 18 | 18 | 2 | 8 | | 3 | | 2 | 1 | | 109 |
| Women guests | 87 | 45 | 38 | 14 | 36 | 5 | 13 | 7 | 4 | 2 | | 251 |
| Totals | 424 | 173 | 183 | 41 | 106 | 9 | 36 | 17 | 14 | 10 | 1 | 1,014 |

and presented each year that do not get through the District channels into the national competition, at least in certain Districts. He emphasized the committee's hope "that a much larger number of Student Branch papers will be presented each year for the national competition."

President Farmer made the prize awards to those prize winners who were present.

### CHARTER MEMBER CHARLES L. CLARKE RECEIVES SPECIAL HONORS

In recognition of the fact that he is a sole survivor from among the 71 leaders of their time who on May 13, 1884, organized the American Institute of Electrical Engineers, special honors were accorded to Charles Lorenzo Clarke (A'84, F'12) of Newton, Mass. This was a special feature of the annual meeting. On behalf of the Institute, President Farmer presented to Mr. Clarke a scroll bearing the inscription "The Members of the American Institute of Electrical Engineers assembled in convention at Swampscott, Mass., June 24–28, 1940, hereby convey to Charles Lorenzo Clarke, sole surviving charter member, their appreciation of his long-continued association with the Institute, and extend to him their felicitations and best wishes."

Obviously deeply moved, but apparently in good health and spirit in spite of his 87 years, Mr. Clarke in accepting the scroll from President Farmer responded as follows:

"Mr. President and brothers of the American Institute of Electrical Engineers. It is a heartfelt pleasure to receive this welcome and testimonial from my professional associates, which I take not only for myself, but in spirit for the other 70 charter members, now gone, by whom the Institute was founded on April 15, 1884; became operatively organized on May 13; and began functioning at its first convention in October of the same year during the International Electrical Exhibition at Philadelphia.

"The faithfulness and ability with which the affairs of the Institute have been conducted for the good of its members, during the 56 years of its life, and the resulting benefits to mankind, are reflected in the increase in members from the original 71, until now they number more than 15,000 in this country alone, and exceed 17,000 altogether; while the benefits are obvious on every hand throughout the world and too vast to be recounted.

"The Institute was founded and has prospered to its present highly useful estate under the fostering protection of a government in a land of freedom bequeathed to us by our forefathers. May those who succeed us continue its growth and usefulness under like conditions.

"I wish for you all a continued well-being consonant with your own just good, also for the good of our country."

### AIEE 1939 LAMME MEDAL PRESENTED TO NORMAN W. STORER

"For meritorious achievement in the development of apparatus and machinery for electrical transportation," the 12th AIEE Lamme Gold Medal was presented to Norman W. Storer (A'95, F'13) retired consulting railway engineer of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. President Farmer made the presentation to Mr. Storer as a feature of the annual meeting. Preceding the actual presentation, Chairman W. B. Kouwenhoven of the Lamme Medal committee reviewed the background of the award, and A. M. Dudley, acting for C. A. Powel of the committee, outlined the career of Medalist Storer. Essentially full text of these various presentations will be found elsewhere in this issue.

*Other Lamme Medal Awards.* In addition to the Institute's award, the late Benjamin Garver Lamme provided for similar awards to be made by the Society for the Promotion of Engineering Education, and by Ohio State University.

The SPEE Lamme Medal for 1939 was awarded to Doctor Andrey Abraham Potter, dean of the schools of engineering and director of the Engineering Experiment Station at Purdue University, "for his leadership in the advancement of the profession of engineering; for his devotion to high standards of teaching and his contributions to the development of engineering education; for his understanding of human nature and sympathetic interest in the work of his associates and students, for his sound judgment and skill as an engineer, and for his untiring efforts in developing co-operative relations between engineering colleges and industry."

The Ohio State University Lamme Medal for 1939 is awarded each year to an alumnus of the University who distinguishes himself in the field of engineering. The 1939 award was made June 10 at commencement exercises to Lawrence Eugene Barringer, engineer in charge of insulations of the General Electric Company, Schenectady, N. Y.

### PRESIDENT'S ADDRESS

President Farmer's interesting and illuminating address on the subject of "Standardization and the Institute," presented at the annual meeting, is scheduled for publication in full in an early issue of ELECTRICAL ENGINEERING.

**Recent Summer Convention Attendance**

| | | | |
|---|---|---|---|
| 1940 | Swampscott, Mass. | *(1) | 1,014 |
| 1939 | San Francisco, Calif. | (8) | 940 |
| 1938 | Washington, D. C. | (2) | 825 |
| 1937 | Milwaukee, Wis. | (5) | 1,067 |
| 1936 | Pasadena, Calif. | (8) | 715 |
| 1935 | Ithaca, N. Y. | (1) | 904 |
| 1934 | Hot Springs, Va. | (4) | 351 |
| 1933 | Chicago, Ill. | (5) | 968 |
| 1932 | Cleveland, Ohio | (2) | 1,022 |
| 1931 | Asheville, N. C. | (4) | 525 |

* District numbers in parentheses.

## Other Convention Features

The ten technical sessions of the summer convention program proceeded approximately as scheduled in the June issue of ELECTRICAL ENGINEERING. Six technical conferences featured the program; reports of five of these are given elsewhere in this issue. The report of the convention meeting of the Institute's board of directors also appears elsewhere.

### FORUM HELD JOINTLY WITH AEC

Continuing the popular procedure of recent years, a "general session" was provided in the Swampscott program, this time with the active collaboration of American Engineering Council under the leadership of its president Colonel Alonzo J. Hammond. All of Thursday forenoon was devoted to this session, and no other sessions were held in parallel. Speaking from opposing viewpoints on the session topic "Transportation as a Social Problem," Colonel William J. Wilgus and Colonel Robert F. Henry held the absorbed interest of a heavily attended meeting.

Colonel Wilgus, well-known consulting engineer and former vice-president and chief engineer of the New York Central Railroad, sincerely and effectively spoke in behalf of government operation of all railroads, on general principles but especially as an allegedly vital factor in national defense. Colonel Henry, assistant to the president of the Association of American Railroads and a lawyer by profession, presented a compelling argument in support of continuing the American ideal of free enterprise and individual responsibility, with special reference to the railroads. Sentiment at Swampscott was strongly in support of Colonel Henry's position. The texts of both these challenging addresses are scheduled for publication in an early issue of ELECTRICAL ENGINEERING.

### ENTERTAINMENT AND SPORTS

In spite of prevailing inclement weather which interfered with scheduled outdoor activities, conventioneers were kept busy and happy during otherwise leisure moments by the programs provided by the local committees. These included sailing, boat races, and trips to any of the numerous nearby points of scenic, historic, or technical interest.

Principal feature of the general entertainment program was a banquet dance held Thursday evening in the enormous main dining room of the New Ocean House. There, Past Vice-President William H. Timbie gave one of his inimitable performances as toastmaster, and addresses were given by President Karl T. Compton of Massachusetts Institute of Technology and Laurence A. Hawkins, executive engineer of the General Electric Company's Research Laboratory. President Compton pointed out the glaring necessity for effective national defense measures as compared with those that actually have been carried out by Federal Government administrative agencies during recent years, and criticized the failure to accumulate adequate supplies of strategic metals necessary for national defense. Mr. Hawkins emphasized the importance of research and engineering as vital elements in effective national defense developments. His address is scheduled for early publication in ELECTRICAL ENGINEERING.

Although a wealth in value and variety of prizes was provided by the local committees, the pressure of other convention activities combined with discouraging weather greatly reduced the participation in the various competitions. Winners in the principal events were as follows:

The Mershon Golf Trophy, available for national competition among Institute members on the basis of match play and handicap, was won by H. A. McCrea of Boston, Mass.; H. E. Wulfing of Chicago was runner up. Mr. McCrea thus becomes the fifth member to have his name engraved upon the present trophy, which is the third

cup donated by Past President Ralph Mershon. This trophy remains on display at Institute headquarters.

The Lee trophy, presented in 1932 by the late Past President W. S. Lee, is awarded each year to the member having the lowest net score for 36 holes, and must be won twice by the same player for permanent possession. At Swampscott, Mr. Wulfing won the Lee trophy, and Mr. McCrea and C. H. Sanderson of New York were tied as runners up. Mr. Wulfing is the eighth member to win a leg on the cup, and the privilege of having his name engraved on it.

In the tennis competitions, C. B. Oler of New York won the Mershon Trophy for men's singles, with L. T. Shilzneck of Lynn, Mass., as runner up. The mixed-doubles competition was won by Mr. and Mrs. F. J. Groat of New York, Mrs. Groat winning also the women's singles. Other competitions featuring attractive prizes included a wide variety of golfing events for men and women, a horseshoe-pitching tournament, a bowling tournament, a table-tennis tournament, and yacht races. In the last-mentioned, crews of the boats participating were made up of AIEE members from among the convention group, although the nonmember owners received the prizes.

# Annual Conference of Officers, Delegates, and Members Held at Swampscott, Mass.

To provide more time for the discussion of Institute affairs, the first three afternoons of the convention week this year were devoted to the sessions of the annual conference of officers, delegates, and members. The conference was held under the joint sponsorship of the AIEE committees on Sections and Student Branches, the Monday and Wednesday afternoon sessions being devoted to Section and general matters with Chairman H. H. Race of the Sections committee presiding, and the Tuesday afternoon session to Student Branch matters with Chairman R. W. Sorensen of the committee on Student Branches presiding.

Attendance at the Monday and Wednesday afternoon session averaged about 100 and the attendance on Tuesday afternoon was about 40. There were present delegates from 66 of the Institute's 70 sections, 9 of the 10 District secretaries, counselor delegates from 8 of the 9 Districts in which committees on student activities have been organized, and others interested in the Institute's organization affairs. The Erie, Mexico, San Antonio, and Saskatchewan sections were not represented. The secretary of District 9 was not present and no counselor delegate was present from District 3.

The program for the conference sessions was carried out as follows:

**Monday Afternoon, June 24, 2:00 p.m.**

Opening remarks—President F. Malcolm Farmer

1. Report on meeting of Sections committee held in New York, January 23, 1940, M. S. Coover, secretary
2. Term of Student enrollment, and election to regular membership, W. G. Knickerbocker, chairman, Michigan Section
3. Publication policies, I. Melville Stein, chairman, publication committee
4. Procedure in connection with applications for Fellow grade, A. E. Knowlton, vice-chairman, board of examiners

**Tuesday Afternoon, June 25, 2:00 p.m.**

Conference on Student Branch activities

**Wednesday Afternoon, June 26, 2:00 p.m.**

1. Status of the proposed Model Law for licensing engineers, C. R. Beardsley, chairman, committee on legislation affecting the engineering profession
2. Section activities—summaries of questionnaires, R. M. Pfalzgraff and W. B. Morton
3. Miscellaneous Section problems
   - *a.* Junior engineer activities, F. Ellis Johnson, chairman, committee on education
   - *b.* Problems incident to the formation of sub-Sections
   - *c.* Methods for serving members who live far from the usual Section meeting places
   - *d.* Methods for welcoming new members and making them "feel at home"
   - *e.* General discussion of Section activities

Before introducing President Farmer, Chairman Race especially welcomed delegates from the Institute's new Sections (Charleston, El Paso, South Carolina).

In his brief remarks of greeting, President Farmer emphasized the importance of these summer-convention conferences to the success of the Institute's activities, and reminded the delegates of their responsibility both as representatives of their several Sections and as individual leaders in Institute activities. He cited the conference as constituting one of the Institute's channels of contact with its individual members, other channels being represented by the national officers periodically elected from among the membership in the various Districts.

Professor Coover reported that the interim activities of the Sections committee were adequately reflected in reports already published in ELECTRICAL ENGINEERING.

### STUDENT ENROLLMENT

The discussion of the topic of student enrollment—the length of time following graduation for which Institute affiliation as an Enrolled Student should be allowed to continue—centered primarily around the question of some special provision to take care of midyear graduates. It was the general consensus that present membership regulations adequately provide for the June graduate by giving him nearly a year (until the following May 1) for the continuance of his student status. Opinions, however, did favor some modification of regulation more equitably to accommodate Enrolled Students graduated at times other than June, particularly the February or midyear group. A special committee appointed at the Monday session by Chairman Race to consider this question and to draft appropriate recommendations brought in the following recommendation:

"To provide equal privileges for those students who graduate at some time other than at the end of a regularly recognized year, the committee recommends that this meeting ask the board of directors to rule, or if necessary to have the bylaws amended, so that the student status of those graduating during the regular academic year can be considered to continue until the end of the regularly recognized academic year, thus entitling such students to the privileges enumerated in sections 53 and 57 of the bylaws covering Institute student enrollment and transfer to Associate membership."

This recommendation, having in the meantime been discussed and approved by the intervening conference session on student activities, was unanimously adopted. It was approved by the board of directors on June 27.

### PUBLICATION POLICIES

Chairman I. Melville Stein of the publication committee presented a digest of certain proposals that have been approved by the publication committee and recommended for adoption for the improvement of the Institute's publication services to its members. Following an explanation by Mr. Stein of the nature and significance of these proposals, and a fairly detailed discussion of them from the floor, each of the several proposals was separately voted upon and endorsed either unanimously or by a substantial majority. As these same proposals subsequently were approved by the board of directors at its Swampscott meeting June 27, a full and detailed exposition of them will be found elsewhere in this issue.

### FELLOW-GRADE APPLICATIONS

At the request of the Sections committee, and on behalf of the AIEE board of examiners, Vice-Chairman A. E. Knowlton of the board of examiners presented before the conference a comprehensive explanation of the procedure required of the board of examiners by the current constitutional and bylaw requirements relating to membership applications, especially with reference to transfer to the grade of Fellow. Current discussion of this general subject seems to center around the insistent proposal from some active Sections that modifications should be made in the procedure with reference to the transfer to Fellow grade that would permit local Section groups to handle such transfers on an invitational or proposal basis without the knowledge or participation of the proposed transferee. This has given rise to requests for "informal" reviews and advance tentative decisions on the part of the board of examiners. Any such "informal" preliminary actions on the part of the board of examiners were clearly shown by Mr. Knowlton to be contrary to existing constitutional and bylaw requirements. Mr. Knowlton pointed out that "if the constitution were to be changed to accord with the objectives of those who desired to see an increase in membership of the Fellow grade, the board of examiners would, of course, then set up rules and practice which would carry out the literal instructions of the revised constitution."

Following an extended discussion of various aspects of this question, Chairman Race appointed a special committee to confer with Mr. Knowlton incidental to the preparation of some specific proposal embracing the expressed desires of the various delegates. This committee reported at the Wednesday session, not with specific recommended proposals, but with a variety of possible modifications, presented for the purpose of drawing out the views and opinions of the various delegates. Further and extensive discussion ensued, leading ultimately to a divided vote recommending to the board of directors that an appropriate

committee be appointed to give further and specialized study to the matter of membership requirements relating to transfers to grade of Fellow and to report to the Sections committee subsequently concerning their findings and recommendations. Following this action an informal show of hands indicated a large majority to be in favor of providing two parallel avenues for transfer to grade of Fellow: (*a*) by direct application of the individual as it was until two years ago, and (*b*) by invitation resulting from sponsorship of five Fellows who could furnish a complete record for the board of examiners without requiring the individual's knowledge or signature. (Subsequently, the board of directors referred the question to the board of examiners "for consideration and report.")

### SECTION ACTIVITIES

To facilitate the exchange of useful information between Sections, C. A. Faust of Mansfield, Ohio, recently prepared and circulated to all Sections on behalf of the Sections committee a questionnaire concerning Section activities. Of the 70 Sections receiving this questionnaire, 54 were sufficiently interested to respond to it. These responses have been co-ordinated and summarized on behalf of the Sections committee by W. B. Morton of the Philadelphia Section and R. M. Pfalzgraff of the Lynn Section. For information and discussion, these summaries in mimeographed form were distributed to delegates at Swampscott. A digest of the salient points probably will be included in an early issue of ELECTRICAL ENGINEERING, and subsequently it is planned to incorporate the information into a revised edition of the booklet on Section activities which, in due course, will be available to Section officers and others interested.

The formation of sub-Sections is one of the most promising activities for promotion of interest, especially in territories having several centers of membership concentration. Several sub-Sections or joint-sub-Sections are being considered.

### LICENSING OF ENGINEERS

Concerning the present status of the proposed Model Law for the licensing of engineers, and of the engineering-license situation in general, Chairman Race read the following communication from C. R. Beardsley, chairman of the AIEE committee on legislation affecting the engineering profession:

"There have been no outstanding developments in the matter of licensing in recent months except that several individual states are drafting laws through engineering committees on which we are represented: for example, California, Missouri, Illinois, and Massachusetts. Some of the ideas and provisions of the Model Law are being worked into these laws where applicable, so that I don't think our work has been entirely in vain.

"What I am most concerned about is this matter of individual Sections following the legislation in their own states as we are doing in New York, so that amendments when proposed may have scrutiny, and support or opposition as may be desirable. . . . The national committee cannot attempt to keep posted on the activities in 48 states and it is only by Sections' activity that this matter may be given the attention that it deserves."

(In connection with this President Farmer had written a letter on April 26 to Section chairmen in which he again urged them to appoint committees on legislation charged with keeping informed on proposals in their states, to present the facts to their membership, and to inform the national committee on legislation and developments.)

"We have received quite a bit of comment and suggestion for alteration to the Model Law, but have not wished to be premature in making a revision. However, we propose to do that ultimately. It is quite possible that after the American Engineering Council gets reorganized, it may be possible to formalize the representations by other engineering societies and work toward a more uniform Model Law composing some of the difficulties and divergencies which now exist."

### SECTION AID TO JUNIOR ENGINEERS

Serious consideration is being given by Engineers' Council for Professional Development and by the professional societies to plans for helping junior or young engineers advance in the profession during the first two years after graduation. Thinking that specific programs for their education and development would be welcomed by such young men, and that possibly various Sections of the AIEE might take the leadership for this work in each locality, the Institute's committee on education recently circulated to all Sections a questionnaire concerning related policy, opinions, and procedure. This project was handled by a special subcommittee consisting of L. W. W. Morrow and K. W. Miller of Chicago, who on behalf of the committee on education, provided a mimeographed report for the edification of the delegates at Swampscott, summarizing the 52 responses that were received from Sections. High lights of this subcommittee's conclusions are as follows:

"It is apparent that Sections, as a whole, have not developed a special program for the development of junior engineers. It is apparent also that each Section is a specific case and that any general program must fit into the conditions each Section encounters.

"Opinions about specialized activities for junior engineers are not positive as to its need, its value, or its reception by junior engineers. It seems obvious that the start of any such work can best be made by having junior engineers participate more actively in regular Section activity. Organized efforts to bring about personal contacts, to get young engineers on committees, to develop some form of paper competition or debates, and to stimulate them to discussion at Section meetings will bring results and possibly, except in special cases, this is as far as Sections can and should go in this work.

"Efforts of Sections to give educational work directly do not appear to be warranted because of the availability of courses already being given by educational institutions and it seems more advisable for Sections to stress the social and professional aspects of development of juniors by having them participate actively in regular Section activities.

"One of the best systems discovered lies in having a senior engineer sponsor a junior engineer. The senior engineer takes the junior to the meeting with him and often invites him to dinner before the meeting and serves as a counselor to the junior. Within limits, this seems to be a splendid activity for Sections to cultivate. . . ."

General discussion of this subject soon broadened out to include a wide range of miscellaneous Section operating problems, but led to no further action.

### COUNSELOR-DELEGATE SESSION

A full afternoon session was devoted to the annual conference of Student Branch counselors and others interested in Student Branch work, this constituting one of the three sessions of the official annual conference of officers, delegates, and members. President-Elect R. W. Sorensen presided as chairman of the Institute's committee on Student Branches.

*Safety.* Emphasizing to Student Branch counselors the importance of adequate safety instruction for engineering students, Frank Thornton, Jr., of Pittsburgh, Pa., reported as follows on behalf of the Institute's committee on safety:

"The national committee on safety of the AIEE believes that students of electrical engineering should become better informed regarding the problems of safe construction, maintenance, and operation of electrical apparatus and equipment. To this end the committee recommends that every Student Branch of the Institute hold one or more meetings during the school year on the subject of electrical safety. Consideration of safety enters into every step of the electrical-engineering field. Extremely interesting discussions can be arranged on the safety provisions in the design of apparatus, the safe methods of installation, safe practices in operation and use of equipment, and on first aid in case of accidents."

That each Branch may have a guide in developing effective meeting programs on the subject of safety, Mr. Thornton reported that his committee is preparing material and recommendations that are intended to be forwarded early this coming fall to the chairman and counselor of each Student Branch. A motion was adopted unanimously urging every Branch to give serious attention to this important topic.

*Prize Regulations for Student Branch Papers.* Considerable time was devoted to an extended discussion of various aspects of the national and District regulations governing student papers intended for submission in competition for District or national prizes. This discussion led to the adoption of the following two recommendations:

(1). That following the first paragraph on page 7 of the AIEE pamphlet of rules governing the award of national and District prizes (edition of January 1937, as amended January 23, 1940), a paragraph be inserted as follows:

"District executive committees shall have the power to fix the dates for closure and award of Branch-paper and graduate-student-paper prizes within its Districts. Unless action is taken by the District executive committee, the dates mentioned in the preceding paragraph of this section shall prevail." (These latter dates are specified as follows: ". . . subsequent to the period covered by the last previous award in the class and prior to the end of the last academic year, July 1 to June 30, inclusive.")

(2). That certain definite changes (specified in detail) be made in the rules governing the award of national and District prizes to provide a basis for the grading of Student papers for such prizes on a basis entirely separate and distinct from the basis used for the judging of regular AIEE technical program papers."

The stated purpose of the first item is "to recognize the diversity of the Student Branch program in the several Districts according to their individual conditions and to enable each District to schedule its prize competition much more effectively in its particular calendar of activity." The second proposal is intended "to recognize that the objective of Student papers differs

## *Future AIEE Meetings*

**Pacific Coast Convention**
Los Angeles, Calif., August 27–30, 1940

**Middle Eastern District Meeting**
Cincinnati, Ohio, October 9–11, 1940

**Winter Convention**
Philadelphia, Pa., January 27–31, 1941

**Great Lakes District Meeting**
Fort Wayne, Ind., April 1941

**North Eastern District Meeting**
Rochester, N. Y., May 1941

**Summer Convention**
Toronto, Can., June 16–20, 1941

from that of adult papers, and to provide a basis for the grading of the former which is more appropriate to its objective. It is not the primary purpose of Student papers to contribute to the technical advancement of the profession. They should constitute a vehicle for the training and stimulation of future contributors to the profession. To this end, greater emphasis on the written presentation and on the exercise of engineering thinking, are to be encouraged, rather than technical value."

These actions subsequently were endorsed and recommended to the board of directors at the closing session of the conference of officers, delegates, and members. At its Swampscott meeting, the board of directors referred these proposals to the AIEE committee on award of institute prizes for reports to the board later.

Among other topics discussed at some length, but without action, were the use of other than monetary awards for District prizes for student papers, and the question of publishing abstracts of District prize papers in ELECTRICAL ENGINEERING.

## Reports of Technical Conferences

Six technical conferences were held in connection with the summer convention at Swampscott, Mass., June 24–28, 1940. Reports of five of these conferences follow. No report of the conference on load swings, held June 25, was available at publication time.

### STANDARDS

This conference, held Tuesday afternoon, June 25, was planned as a continuation of the morning session on standards, with the special object of discussing the principles of short-time ratings of electrical apparatus. This subject is being studied by AIEE coordinating Committee 4 as a continuation of the program initiated at the January 1939 symposium on motor rating. As an outgrowth of the earlier meeting, AIEE Standards No. 1, entitled "General Principles Upon Which Temperature Limits Are Based in the Rating of Electrical Machinery and Apparatus" has now been completely revised and was made available for the first time at this Swampscott meeting.

Two informal papers were presented at the conference, both dealing with methods of rating welding apparatus. R. C. Freeman, who presented the first paper dealing with the rating of welding generators, stressed the importance of designing generators to meet actual customer needs, rather than to comply with an arbitrary short-time rating. In practice, a welding generator must deliver the required welding current under all operating conditions, but it does not need to have the cooling capacity that would be required for a continuous rating at the full current. Due to the intermittent character of hand welding, with delays for changing electrodes, readjusting the work, etc., the generator is idle for a considerable part of the time. Experience indicates, therefore, that actual loads very rarely exceed in severity a duty cycle consisting of alternate periods of 60 per cent time on and 40 per cent time off. Furthermore, the duration of each load cycle is so short that a continuous load equal to the rms equivalent of the duty cycle gives a fair representation of the heat-dissipating requirements.

For these reasons, the proposal was made that welding generators be rated on a 60 per cent duty cycle, or its practical equivalent of a 75 per cent service factor basis. This would require the generator to meet the standard temperature rise for the class of insulation used when operated continuously at 75 per cent of the nameplate current.

Mr. Freeman also presented data on the various methods of measuring temperature rise and stressed the difficulty of obtaining accurate measurements "on the fly" when the 30-minute test or other short-time heat run is required. He pointed out that the thermometer method is particularly inaccurate on short-time tests at high currents, which result in a considerable internal temperature drop through the insulation, and a material time lag of the thermometer behind the actual copper temperature. For these reasons, the proposed continuous test at the service factor rating will give a much more accurate and definite criterion of rating. In conclusion, he presented a tabulation of differences between the thermometer and the resistance method of temperature-rise measurement for several different American makes of welding generator, showing a spread of from 17 to 40 degrees between these two methods of measurement, as compared with 10 degrees recognized in the revised AIEE Standards No. 1. This evidence confirms the data given in Mr. Compton's paper presented at Scranton in October 1939 and that in Mr. Veinott's paper presented at the morning session, to the effect that the resistance method is preferable to the thermometer method for accurate tests, but that appreciably higher rise values must be permitted if present-day d-c machines are to be accepted on a resistance instead of a thermometer-rise basis.

A. U. Welch, who presented the second paper dealing with the rating of welding transformers, gave a careful analysis of various hand-welding duty cycles, and also reached the conclusion that a 60 per cent time on duty cycle gives the most satisfactory representation of the actual service requirements. In the case of a transformer, with its relatively low light-load losses, this duty cycle is simulated by a continuous heat run at 80 per cent of the rated current. Mr. Welch, therefore, proposed that a "service-factor rating" of 80 per cent be used for welding transformers in place of the present practice of short-time ratings, which do not represent actual continuous load, nor give a fair picture of the transformer's ability to meet the actual load requirements without overheating.

In the ensuing discussion, various views were expressed on alternative methods of short-time rating. On the one hand, the facts that temperature limits are common to all types of apparatus and that the all-day output of a machine is generally proportional to its continuous capacity, suggest that machines should be rated on the basis of continuous output at the limiting temperature. In this case, machines may be given some type of overload rating, expressing their reliable peak capacities. On the other hand, the rms method of evaluating duty-cycle loads was stressed as satisfactory for the great majority of all industrial applications, and the desirability of rating the apparatus in terms of its safe available output was shown. These ideas lead at once to the "service-factor rating" method, in which the nameplate rating indicates the always available capacity, while the service factor shows the percentage of the nameplate value which can be carried continuously within the standard temperature limits. The 115 per cent service factor now applied to all general-purpose motors is a case in point, and it was pointed out that the use of a service factor less than unity, as now proposed for welding apparatus, is merely an extension of present well-established practice. L. E. Hildebrand's paper "Duty Cycles and Motor Rating" (*AIEE Trans., vol. 58, 1939, p. 478–83*) was cited in support of this position.

*Co-ordinating Committee 5, Basic Theories and Units.* Reporting upon this subcommittee, which was appointed in April 1940, its chairman, Edward Bennett, presented for consideration a tentative statement of its functions and of the questions before it. (Copies of this report may be obtained from the chairman.) The function of the committee is to bring the resources of the Institute to the support of the movement looking toward agreements upon, and the use of, preferred systems of units. The work immediately before the committee will be informative in nature, designed to bring about a clearer and more widespread understanding of the following topics in the field of electrical units and standards:

(*a*). The principles governing the devising of comprehensive systems of units;

(*b*). The differing and conflicting purposes which are encountered in the devising of systems of units and in the defining of standards;

(*c*). The relative precision of alternative standardizing procedures and sequences;

(*d*). The questions closed by recent international decisions;

(*e*). The questions which are now pending.

Among the pending questions, the following call for consideration. Shall the rationalized or the unrationalized system of electrical units be designated as the preferred system? What further definitions or statements must be adopted in carrying out the standardizing procedure by which the electrical units and standards are to be derived from the mechanical units under the 1933 decision of the General Conference on Weights and Measures. This decision was to the effect that the electrical system of units is to be an absolute system in which the electrical units are derived from the mks mechanical units by assigning to the permeability of free space the value $\mu_0 = 10^{-7}$ in unrationalized units, or $\mu_0 = 4\pi 10^{-7}$ in rationalized units.

An organization meeting of co-ordinating committee 5 held Wednesday afternoon, June 26, gave further consideration to these questions and provided for the appointment of subcommittees to prepare memoranda or reports on a number of the questions.

*Co-ordination of Current Ratings.* The last part of the standards conference was devoted to a discussion of the proper coordination of current ratings of apparatus

connected in series in the same circuit. R. E. Hellmund pointed out that when the load is continuous no particular problem exists as long as the continuous ratings of all devices and conductors are equal to or larger than the continuous load current. However, circuits with uniform loads are the exception rather than the rule and in most applications the load is intermittent or varying. A simple case of a motor with intermittent load was discussed for the purpose of illustration. With the load coming on and off, all the devices and conductors heat and cool alternately, but on account of their different sizes they usually have time constants varying over a wide range. This in turn leads to different degrees of heating during varying intermittent service. The usual practice with short-time and intermittently rated motors is to apply conductors having a continuous rating equal to the short-time rating of the motor. While this practice is safe, there is some question as to its economy. Curves were shown indicating that even though the time constant of the conductor is smaller than that of the motor, worthwhile economies can nevertheless be accomplished. Other curves were shown indicating that if the conductor has the same short-time rating as the motor, the heating of the conductor will be safe for all types of intermittent loads. Similar conditions apply to other series-connected apparatus, because as a rule all such apparatus has time constants smaller than that of the motor. It was stated that worthwhile economies very likely could be accomplished by further study and that particular attention should be given to thermal devices connected into the circuit for protecting either the motor or the conductors.

Subsequent discussion showed that very little is known about the effect of short-time heating of rubber used in wires and cables to temperatures above those considered safe for continuous service. Investigations along these lines seem desirable. It was suggested that a standards co-ordinating committee to study these questions in co-operation with other interested committees might be of assistance.

### STATISTICAL METHODS

More than 100 attended the conference, two-thirds of which was devoted to the four scheduled papers, and the remaining third to general discussion.

The first paper was presented by H. F. Dodge, Bell Telephone Laboratories. He pointed out that any practical discussion of quality or its measurements must deal with variability. The quality of a finished product varies from unit to unit. No matter how great the effort or how refined the manufacturing process, no two units are exactly alike. For this reason, the quality of any mass of product, in terms of a single characteristic, is fundamentally a frequency distribution. Recognizing this fact, tolerance limits are set in terms of such a frequency variation. The magnitude of limits or their location is based entirely upon practical experience. By means of a sampling demonstrator, Mr. Dodge then showed what distributions look like and the ways in which they can be expected to vary under uniform conditions of sampling.

Next, control charts were presented which showed the improvement in apparatus obtained by analyzing variations in the product which fell outside of the established frequency diagram limits. In the use of these charts, it was pointed out that variations in the product beyond those expected nearly always indicated the presence of a source of variation large enough to be worth finding. On the other hand, variation of the product within the tolerance limits indicated there were no outstanding causes of trouble which were economical to eliminate. In the last part of his talk, the speaker pointed out that there is another method of controlling quality besides taking measurements on specific characteristics of the product. This method is that of setting tolerance limits on the "per cent defective." By means of sampling demonstrator typical variations in the "per cent defective" were shown. This concluded Mr. Dodge's talk and introduced that of J. A. Davidson, Western Electric Company.

First, Mr. Davidson demonstrated the magnitude of the inspection problem encountered in the manufacture of telephone apparatus. He showed the typical per-cent-rejection chart used for reference by Western Electric Company officials in controlling the quality of their apparatus. The left-hand side of this chart contained a typical per-cent-rejection record with dotted limit lines to define abnormal change in quality. On the right-hand side were data pertaining to the last point placed on the quality curve. The data showed the numbers of faults of various types and the demerit values applied to such faults. Lantern slides and special examples were then used to show the exact process of putting into operation statistical quality-control methods. It is to be noted that the defective material was divided into subgroups. In the subgroup which dealt with very serious quality defects the number of parts defective were multiplied by a constant which arbitrarily made the number defective appear larger than it really was. In the subgroup dealing with rejections of not quite so serious a character, the actual number defective was multiplied by a lesser factor. Hence, in the building up of the per-cent-rejection limits and other per-cent-rejection data, serious instances of poor quality were given much more weight than unimportant departures from good quality.

The demerits applied under this system are 100 demerits for very serious faults, 50 demerits for serious faults, 10 demerits for moderately serious faults, and 1 demerit for nonserious faults. This detailed analysis was very helpful to that part of the audience interested in the actual steps of applying quality control to a mass-production project.

Under the subject "Building up of Engineering Tolerances", R. E. Wareham, General Electric Company, showed the effects of adding together variations in structure. Using as an example the diameter of a bearing and shaft, it was shown that the least defective product could easily result in random selection of shafts to combine with random selection of bearings. This example demonstrated the fact that much engineering thought can well be given to the most economic way of assembling apparatus from the point of view of specified tolerance limits of the component parts and specified per-cent-acceptance limits of the final assembly.

Harold R. Bellinson, who was sent to the conference from the Aberdeen Proving Ground by the United States Army, discussed the aspects of designing experiments properly to get the maximum information for the minimum of data. First, Mr. Bellinson defined the conception of a population. It was pointed out that once the idea of a population is achieved, the necessary step is to set up an hypothesis that two sets of data come from the same population. An experiment is then made to determine whether they do not come from the same population. When the experiment yields a significant difference in the two sets of data, it can be concluded that there is little probability that they do come from the same population. Unless significant differences are found, the original hypothesis is considered to hold good.

Mr. Bellinson next emphasized the importance of sampling so as to obtain randomness. Randomness implies the lack of bias in the original observation and the fact that each observation will be completely independent of all other observations. Sensitivity of an experiment can be increased either by increasing the number of observations or by eliminating sources of error. Where economical and possible, control of test conditions is used in eliminating sources of errors; uncontrollable factors can best be handled by either randomizing or balancing. If either of these is done, the sensitivity of the experiment may be changed and if such is the case, the experiment should be modified so that the final results will be returned to the desired degree of sensitivity.

Summing up all four papers, it may be said that they served as an excellent introduction of statistics into the fields of quality control, engineering, and research. Available for copying by members of the conference was a bibliography of reading matter on the subject of statistics. Furthermore, the members of the conference were presented by the American Standards Association with the May issue of "Industrial Standardization" containing J. Gaillard's review of Doctor W. A. Shewhart's latest book "Statistical Methods From the Viewpoint of Quality Control".

During the general discussion period, a number of interesting points were brought out. For example, under certain conditions, the sampling method of quality control may be more accurate than the 100 per cent inspection method. The application of statistics to quality control introduces the thought of improving the over-all quality of apparatus as compared to the typical inspection method which merely sorts the good units of apparatus from the bad. It was emphasized that men in the factory at the work bench react quickly and favorably to the idea of improvement in quality.

Doctor Shewhart stated that in research work the trend of the points toward limit lines can often be used as a useful indicator even before the limit-line boundaries are actually reached. It was brought out very clearly by P. L. Alger and Doctor Shewhart that statistical control plays a very large and relatively unexplored part in the field of purchasing specifications. During a period of unsettled world conditions, such as we are at present encountering, it is desirable to buy raw material with the minimum of delay and the maximum of economy. The statistical technique should greatly aid in achieving such efficiency. It was therefore unanimously recommended by a vote of those present that Mr. Alger convey to the

Standards Committee of the AIEE the recommendation that the committee undertake activities directed toward the introduction of the statistical technique in the control of quality of purchased material.

### PRINCIPLES OF NONLINEAR ANALYSIS

The increasing importance of nonlinear problems in all phases of engineering research led to the organization of this technical conference by the committee on basic sciences, as a first attempt to present a rather comprehensive picture of the various mathematical methods available in nonlinear analysis. In order to guide the general discussion four prominent authors had prepared informal papers illustrating these methods.

Professor E. G. Keller of the University of Texas presented briefly six analytical methods, illustrating each one with a practical application taken from his experience with the General Electric Company. Starting with nonlinear celestial problems first solved by Euler, he ended with the most modern methods developed by the Russian, Galerkin. His electrical illustrations referred to problems of shunting of synchronous machines, transients in saturated iron circuits, declaration of rotors, and others, for which an extensive bibliography had been prepared in mimeographed form. Professor Keller also pointed out the difficulties to be encountered in actual solutions and called attention to the types of problems to which the different methods are particularly applicable.

A. Preisman of the RCA Institutes, New York, N. Y., explained the principles of graphical analysis, illustrating the method mainly with examples involving electron-tube circuits. Starting from simple resistive circuits, he then applied the method to electron-tube circuits with inductive and capacitive branches so that nonlinear differential equations resulted which he solved by a graphical step-by-step method, obtaining transient as well as steady state response.

Professor J. B. Scarborough of the United States Naval Academy presented the principles of the step-by-step numerical solution of nonlinear differential equations of the first and second order with the necessary checks to assure high accuracy, which is certainly one of the major advantages of numerical solutions. He illustrated the methods by means of three examples for which brief mimeographed tables had been prepared.

Professor S. H. Caldwell of the Massachusetts Institute of Technology finally gave a brief account of the principles involved in the use of the differential analyzer in the solution of differential equations of any order, linear or nonlinear. He illustrated the setting up of the differential analyzer for a nonlinear problem that Professor Scarborough had discussed. To show the wide applicability, Professor Caldwell chose four different problems, the first three with nonlinear resistance, inductance, capacitance, respectively, and the fourth with a combination of all three elements. He briefly indicated the main trouble with the present differential analyzer, particularly the amount of time needed in "putting in" the problem, and gave an informal preview of the principles of an improved analyzer which is in the state of construction.

The discussion was extremely interesting and brought out additional points, thus emphasizing the advantages of a free discussion on problems so definitely in the frontier of progress. The attendance of about 60 and the interest displayed were most gratifying and certainly dispelled any fear of bringing even most advanced topics before special groups such as usually gather for properly announced technical conferences.

### TEST CODES

The technical conference on test codes was attended by approximately 30 people. The need for master test codes on general subjects which are common to different types of machines was discussed. The conference considered a report of the chairman of the subcommittee on d-c machines in regard to the status of the recently revised test code for d-c machines. The first draft of the preliminary test codes for single phase, a-c motor which has just been completed by the special subcommittee appointed for this purpose, was reviewed.

### DIELECTRIC MEASUREMENTS IN THE FIELD

Over 60 members attended the conference on dielectric measurements in the field, which was sponsored by a subcommittee of the instruments and measurements committee. The success of the conference was due in large measure to the participation of many operating-company engineers who spoke freely on their experiences in the field. Seven prepared reports were presented as indicated by the following.

"A-C and D-C Measurements on Bushings, Armatures and Cables", by A. L. Brownlee, Commonwealth Edison Company. From test data in the form of dielectric power-factor-voltage curves, it is concluded that valuable information is obtained from measurements made at or above the rated voltage of the apparatus. Supplementary high potential tests are made before removing armatures from service. D-c measurements are as yet inconclusive, and further work is necessary.

"Power-Factor and Capacitance Measurements on Insulation of Distribution Transformers", by G. E. Quinn, Consolidated Edison Company of New York, Inc. Measurements of insulation power factor and capacity made during heating runs at 73 degrees centigrade are valuable in showing the influence of moisture. Temperature correction factors for the insulation properties are dependent on moisture content. The presence of ionization is shown by tests made at rated voltage.

"Insulation Tests by the Wattmeter Method", by F. C. Doble, Doble Engineering Company. Power-factor measurements at 10 kv by the wattmeter method were first made on bushings, and these tests were found to give a reliable indication of defective insulation. This method has been extended to transformers, circuit breakers, cables, and other equipment, and many thousands of pieces of apparatus are now being tested annually. Power-factor limits have been set up for questionable and defective insulation for various equipments. Localized insulation defects are determined by "hot-collar" tests which allow the application of high gradients to selected portions of the insulation.

"Insulation Testing in the Field", by H. R. Selfridge, Central Division, New England Power Company. Prior to 1930, low-voltage d-c resistance tests were successfully used to reveal the formation of creepage paths in type *SI* bushings. Insulation loss tests at 10 kv by the wattmeter method were next used to indicate the presence of moisture in condenser-type bushings. Yearly tests made on many bushings rated up to 110 kv have made possible a great reduction in outages. The tests are now also applied to metering equipment, transformers, and stack insulators.

"Field Tests on Oil Circuit Breakers", by G. L. A. Thomson, Public Service Electric and Gas Company (communicated). Oil circuit breakers are tested annually by means of two power-factor potentiometers operating at 10 kv and 70 cycles. The insulation losses are corrected to 40 degrees centigrade, and rejection values for breakers of various sizes have been selected. All indications showing poor oil, rods, insulators, bus supports, etc., are taken into account.

"A-C and D-C Measurements on Porcelain Pin-Type Insulators", by R. F. Field, General Radio Company. Insulation power factors and capacitances at very low frequencies are calculable by well-known methods from d-c resistance-time curves. From experimental data on insulators, it is shown that moisture increases the power factor and capacity in the low-frequency range and changes the temperature coefficient of power factor. Moisture in restricted parts of certain composite commercial insulations is not always harmful, however.

"Practical Aspects of Field Testing of Insulation by the Resistance-Time Method", by E. B. Curdts, The Narragansett Electric Company. Resistance-time tests were used to study the behavior of a transformer bank, one unit of which had been contaminated by water, flushed out, and put back into service. The conclusion is that such measurements provide a promising method to supplement the power-factor tests in indicating the presence of moisture and operating reliability.

In the subsequent informal discussion, I. W. Gross, American Gas and Electric Company reviewed briefly the results of his field testing as covered in papers published in *Electrical World* (1934) and ELECTRICAL ENGINEERING (1938). He said that each year the work is being extended profitably to additional types of electrical apparatus. C. F. Hill, Westinghouse Electric and Manufacturing Company, stated that the manufacturer's engineer is interested in field testing because he is sometimes invited to assist in field testing, and because he is responsible for the bench marks with which later field test results are compared. P. L. Betz, in a letter read by H. C. Louis, Consolidated Gas Electric Light and Power Company, recommended that more papers on field testing be published, and that complete circuit arrangements be described.

T. B. Whitson, James G. Biddle Company, pointed out that insulation containing moisture exhibits a more nearly constant resistance-time curve and a greater decrease in resistance with voltage increase than dry insulation. G. M. L. Sommerman, American Steel and Wire Company, stated that some insulations containing very large amounts of moisture are characterized by a decreasing resistivity-time curve in accordance with the early experiments of Evershed.

H. C. Hamilton, Boston Edison Company, pointed out that it would be very desirable to have a test method which would indicate defective insulation between turns of apparatus windings.

G. Keinath, consulting engineer, in a later communication, suggested that power-factor recording equipment operating at full line voltage be used in field tests, in view of the advantages of such a test method in indicating ionization.

The authors of the reports and discussions agreed to submit abstracts of their presentations for mimeographing and distribution to those who attended the conference and other interested members. In closing the conference, it was pointed out that plans were being made for the presentation of a symposium of papers on field testing of insulation in the near future.

## Board of Directors Meets at Swampscott

The regular meeting of the AIEE board of directors was held at the New Ocean House, Swampscott, Mass., on June 27, 1940, during the annual summer convention of the Institute.

Chairman I. Melville Stein of the publication committee presented a report of the committee on the publication policy of the Institute and six specific recommendations for modifications. The board approved the recommendations of the publication committee as submitted. (The changes thus adopted are described on pages 331–2.)

Upon recommendation of the standards committee, the board approved for immediate publication the 1940 revision of AIEE Standards No. 45, "Recommended Practice for Electrical Installations on Shipboard," which had been prepared and submitted by the committee on applications to marine work.

Upon recommendation of the conference of Student Branch counselors and the conference of officers, delegates, and members, held during the 1940 summer convention, the board voted to change the period of time in which Enrolled Students may apply for admission to the Associate grade without payment of the entrance fee, to permit students graduating any time during the academic year (July 1 to June 30) to transfer until May 1 of the succeeding academic year with waiver of the entrance fee. This action was referred to the committee on constitution and bylaws for the necessary revision of the bylaws. The purpose of this change was "to extend to students graduating before the end of the academic year essentially the same period of grace now provided for June graduates".

Amendments to the rules governing the awards of national and District prizes of the Institute, which were recommended by the conference of Student Branch counselors and the conference of officers, delegates, and members, were referred to the committee on award of Institute prizes for report to the board of directors.

Recommendations adopted at the conference of officers, delegates, and members concerning procedure for transfer to the grade of Fellow in the Institute were referred to the board of examiners for consideration and report.

Upon request of the Charleston Section and recommendation of the Sections committee, the name of that Section was changed to "West Virginia Section".

The board approved the certificate of incorporation of the Engineering Societies Personnel Service, Inc., as a nonprofit membership corporation under the laws of the State of New York, authorized the termination of the joint agreement of 1923 with other societies under which the Engineering Societies Employment Service was established and the transfer of its activities to the new corporation, and authorized the president to appoint the AIEE representative on the board of directors of the Engineering Societies Personnel Service, Inc.

Resolutions expressing the board's appreciation of the effective services of the 1940 summer convention committee and its subcommittees, and of the women's entertainment committee, were adopted; also a resolution to the president of the New Ocean House in appreciation of the care taken for the comfort of those in attendance and for the excellent facilities provided for the convention events.

A motion was adopted, recording the board's appreciation of the effective services rendered during the past year by President F. Malcolm Farmer, who responded with an expression of his pleasure in the association with the members of the board.

Resolutions were adopted endorsing the defense preparedness program of the government and offering the services of the Institute in connection therewith, to be sent to the President of the United States. (See left.)

Other actions taken included the following:

Minutes of the meeting of the board of directors held on May 24, 1940, were approved.

A report was presented and approved of a meeting of the board of examiners held on June 13, 1940. Upon recommendation of the board of examiners, the following actions were taken: 2 applicants transferred to the grade of Fellow; 21 applicants transferred and 13 elected to the grade of Member; 107 elected to the grade of Associate; 64 Students were enrolled.

Expenditures in June, amounting to $20,521.37, were reported by the finance committee and approved.

Those present were:

*President*—F. Malcolm Farmer, New York, N. Y.

*Vice-Presidents*—T. F. Barton, New York, N. Y.; C. L. Dawes, Cambridge, Mass.; H. W. Hitchcock, Los Angeles, Calif.; A. H. Lovell, Ann Arbor, Mich.; F. R. Maxwell, Jr., University, Ala.; C. T. Sinclair, Pittsburgh, Pa.; J. M. Thomson, Toronto, Ont.

*Directors*—C. R. Beardsley, H. S. Osborne, New York, N. Y.; Mark Eldredge, Memphis, Tenn.; R. E. Hellmund, East Pittsburgh, Pa.; F. H. Lane, L. R. Mapes, Chicago, Ill.; K. B. McEachron, Pittsfield, Mass.; F. J. Meyer, Oklahoma City, Okla.; D. C. Prince, Schenectady, N. Y.; R. W. Sorensen, Pasadena, Calif.

*National Treasurer*—W. I. Slichter, New York, N. Y.

*National Secretary*—H. H. Henline, New York, N. Y.

*Present by invitation:* A. J. Hammond, president, American Engineering Council; A. W. Berresford, D. C. Jackson, Charles F. Scott, past presidents, AIEE; M. S. Coover, Everett S. Lee, R. G. Warner, officers-elect; I. Melville Stein, chairman, publication committee.

Regrets were received from:

*Members of the board*—W. H. Harrison and John C. Parker, past presidents, and A. L. Turner, vice-president.

*Invited guests*—Past Presidents C. A. Adams, H. P. Charlesworth, Frank B. Jewett, A. M. MacCutcheon, and C. E. Skinner.

## Resolutions of the AIEE Board of Directors on National Defense

The board of directors of the American Institute of Electrical Engineers, at a meeting held on June 27, 1940, in connection with the 56th summer convention at Swampscott, Mass., unanimously passed the following Resolutions:

RESOLVED, That the President of the United States be advised that the American Institute of Electrical Engineers believes the principles upon which the government of the United States is founded should be preserved and that the Defense Preparedness Program be approved;

RESOLVED, That the President be advised that the American Institute of Electrical Engineers stands ready to aid in expediting in every possible way the carrying out of this program for the defense of our country;

RESOLVED, That the President be informed that the American Institute of Electrical Engineers and its members have already rendered service in connection with this Defense Preparedness Program through the American Engineering Council and other organizations that correlate all forms of engineering activities, and that this specific action is for the purpose of making known to those responsible for the planning and smooth functioning of the program that the Institute is wholeheartedly supporting it, and is ready and anxious to receive calls for any specific service that can be rendered by its 17,500 members or by any of its committees.

Respectfully submitted,

(*Signed*) F. Malcolm Farmer
*President*

H. H. Henline
*Secretary*

July 12, 1940

# District • • • •

## Middle Eastern District Meeting

Arrangements are rapidly nearing completion for the Middle Eastern District meeting and Student Branch convention, to be held in Cincinnati, Ohio, October 9–11, 1940. Meeting headquarters will be in the Hotel Netherland Plaza, located in the heart of the city.

### ATTRACTIONS OF THE CITY

Cincinnati, known as "The Queen City," is of great beauty and interest. Its famous zoological gardens cover 57 acres of wooded grounds. Its art museum has acquired through the years a collection of old masters and modern paintings. Its university, home of Doctor Herman Schneider's well-known co-operative engineering course, is rated as the largest municipally owned university in the United States with an enrollment of nearly 13,000 students. The city is best known in many quarters for its music and the internationally famous symphony orchestra.

Cincinnati is known as the machine-tool capital of the world, its milling machines, grinders, planers, lathes, radial drills, etc., going to the four corners of the earth. It is noted as a radio center in the fields of manufacturing and broadcasting. Five broadcasting stations, including the former 500,000-watt super-power station WLW, are located in the vicinity. Cincinnati is rated first in the manufacture of soap and electrotypes and is the hub of a highly diversified industrial community of great importance in the present program of national defense. It has many points of interest for engineers.

### TECHNICAL PROGRAM AND INSPECTION TRIPS

As the Cincinnati meeting is the only District meeting of the Institute scheduled for the fall of 1940, the local technical program committee, in co-operation with the national technical program committee, is providing a diversity of live topics calculated to appeal not only to the Sections of District 2 and the adjoining Districts but to many other members. Cincinnati is only overnight from all of the principal centers of Districts 2, 4, 5, and 7 and one day's drive only from most points in District 2.

An inspection trip on Thursday afternoon, October 10, will be taken to the great continuous strip mills and research laboratories of the American Rolling Mill Company at Middletown, Ohio, and on Friday afternoon, October 11, a trip will be made to the flood-proofed Columbia Station of the Cincinnati Gas and Electric Company, and a communications tour to the studio and transmitter of station WLW and the Crosley television station. More information on the technical program and a list of trips are scheduled for the September issue of ELECTRICAL ENGINEERING.

### ENTERTAINMENT AND OTHER ACTIVITIES

Entertainment for all is being arranged. On Wednesday evening, October 9, while the men are occupied at a stag smoker, women guests will visit one of the principal radio studios to witness the presentation of a national feature program. A bridge luncheon for women is scheduled at noon on Wednesday, as well as special inspection trips on Thursday and Friday mornings to the new laboratories of the Kroger Food Foundation and to the Procter and Gamble Company, respectively. Thursday afternoon will be occupied by a musicale and tea in the attractive old colonial home of the late Charles Phelps Taft. This house is now an art museum under the supervision of the Cincinnati Institute of Fine Arts; the famous Taft collections of painting, French enamels, Italian majolica, and Chinese porcelain will be on display.

On Thursday evening is scheduled the banquet and an address by a nationally known speaker, and on Friday afternoon a sightseeing tour for members and their families to points of interest in the city and environs, including the principal parks, zoological gardens, art academy, Rookwood pottery, university, etc.

The Student Branch convention, at which Student members will find an attractive program devoted to their special interest, will be held in connection with the meeting. There will also be held the annual business meetings of the District executive committee and of the District committee on student activities.

# Standards • • •

**Recommended Practice for Electrical Installations on Shipboard.** A revised edition of AIEE Standards No. 45 "Recommended Practice for Electrical Installations on Shipboard (Marine Rules)" has just been issued. These marine recommendations have been drawn up to serve as a guide for the equipment of merchant vessels with electric apparatus for lighting, signaling, communication, power, and propulsion. They indicate what is considered good engineering practice with reference to the safety of the personnel and of the ship itself. This revised edition was developed and approved by the AIEE committee on applications to marine work in May and approved by the board of directors on June 27, 1940. Copies may be obtained from AIEE headquarters, 33 West 39th St., New York, N. Y., at a cost of $1.50 each, with usual 50 per cent discount to AIEE members on single copies only.

**Measurement of Test Voltage in Dielectric Tests.** A completely revised edition of AIEE Standards No. 4 "Measurement of Test Voltage in Dielectric Tests" was issued in June. The revisions include the latest developments in measurement of test voltages and wave shapes—puncture tests, flashover tests and voltage proof tests—the use of alternating current, direct current, and surge generators. An appendix is devoted to testing equipment and arrangement. An extensive bibliography is also included. Price 40 cents per copy; 50 per cent discount to members on single copies.

**Electronic Devices.** At the May 21 meeting of the standards committee a suggestion was approved which calls for the formulation of guiding standards for electronic devices. The joint subcommittee on electronics will be requested actively to undertake the project.

**Vice-Chairman of Standards Committee.** R. T. Henry, of the Buffalo, Niagara and Eastern Power Corporation, has accepted the appointment as vice-chairman of the AIEE standards committee

# Abstracts • • •

**TECHNICAL PAPERS are previewed in this section as they become available in advance pamphlet form. Copies may be obtained on payment of price indicated to the AIEE order department, 33 West 39th Street, New York, N.Y.**

## Basic Sciences

**40-108—Transient Analysis of Completely Transposed Multiconductor Transmission Lines;** *Louis A. Pipes* (*A'37*). *10¢.* Starting with the general equations of the completely transposed $n$-conductor transmission system expressed in matrix form, the equations are subjected to a similarity transformation. This transformation reduces the general equations to a set of $n$ independent equations. These equations are then subjected to a Laplacian transformation and solved subject to the impression of arbitrary electromotive forces at a certain point of the lines. Expressions are obtained for the resulting traveling waves of voltage and current and the velocities of propagation are discussed. (This paper also was presented at the 1940 AIEE summer convention, Swampscott, Mass., June 22–26.)

## Communication

**40-136—Vario-Losser Circuits;** *W. R. Bennett and S. Doba.* *10¢.* Methods are given for the design of circuits using "varistor" elements to secure specified variations of loss as a function of input signal. The types of circuits include compressors and expandors using shunt, series, and lattice networks. Formulas for steady-state transmission and distortion in terms of varistor characteristics are developed.

## Electrical Machinery

**40-120—Some Acceleration Tests on Large Synchronous Pump Motors;** *R. W. Ager* (*A'24*). *10¢.* Acceleration tests on motors may yield very interesting and valuable information. These tests show the behavior of the motor in that region between zero speed and full speed through which each motor must pass every time it is started. The accelerating characteristics of a motor determine the margin by which that motor is able to start and bring its load up to speed in a reasonable length of time under the least favorable conditions which might be encountered. Acceleration tests may also be used in checking theories of operation, correctness of design constants, the presence of any peculiarities in the performance curves, and, in the case of induc-

tion and synchronous machines, any tendency to lock in at a subsynchronous speed. The main tests reported in this paper were made on the large synchronous pump motors used on the Metropolitan Water District aqueduct which is to supply Colorado River water to Southern California. The tests were performed in the field, after the motors had been installed, with the pumps connected, and with normal operating conditions existing.

**40-135—A Generalized Equivalent Circuit in the Theory of Polyphase Commutator Motors;** *W. B. Coulthard* (*M'34*). *10¢.* The novelty in this derivation of the theory of an individual motor by way of a generalized equivalent circuit lies not in the theory, but in the manner of its derivation. Incidental to his classroom lecture work, the author tired of the usual method of treating one motor per lecture, and undertook to derive the general characteristics from a basic principle.

**40-130—Power-Factor Testing of Transformer Insulation;** *J. B. Hodtum* (*M'26*). *10¢.* The term "power-factor testing" of insulation during the past several years has come into wide use. However, it is felt that dissipation factor is a better term because it is directly proportional to the product of its insulation loss and specific inductive capacitance and therefore simplifies the mathematics necessary when analyzing such tests. This paper points out a method for analyzing the results obtained from dissipation-factor tests of transformer insulation. Experimental data, obtained both from transformer tests extending over the past three years and from tests of sample insulation, indicate a definite relation between resistance and capacitance, with varying conditions of temperature and moisture. This relation furnishes a means for determining the condition of the insulation. The physical arrangement of the transformer windings and the type of test equipment used affect the tests and should be considered when interpreting results.

## Instruments and Measurements

**40-131—Behavior of Point Gaps at 60 cycles;** *Jean V. Lebacqz* (*A'40*). *10¢.* This paper covers the result of extensive laboratory work. The results as summarized should be of interest and value to all those who are concerned with the flashover of insulation or of insulators.

**40-128—Braking Magnets for Watt-Hour Meters;** *I. F. Kinnard* (*M'28*) *and J. H. Goss* (*A'35*). *10¢.* It is the purpose of this article to discuss suitable test methods for determining characteristics of braking magnets for watt-hour meters and to review actual test data that have been obtained on magnets of various types and materials. A careful investigation is outlined showing the relationship of coercive force and the ability of the magnet to withstand demagnetizing fields. This investigation covers the demagnetizing effect of surge currents ranging from direct current to those approximating natural lightning. An attempt is made to formulate the requirements of an ideal watt-hour-meter braking magnet and to illustrate how a designer might make a logical choice from materials that are now available.

## Power Generation

**40-132—An Electrical Governor;** *Frank I. Morgan* (*M'39*). *10¢.* The advantages obtained from the application of electrical methods of control to all classes of machinery suggested to inventors the idea of regulating the speed of prime movers by electrical means. Frequent attempts have been made to accomplish this result. Many of these governors were very ingenious, but for one reason or another they never came into general use. The electrical governor described in this paper is the result of several years' effort to develop a practical method of electrically controlling and regulating the speed of hydraulic turbines. The method utilizes a form of frequency meter which measures variations in the frequency (corresponding to changes in speed) of an alternating current supplied by the generator driven by the turbine to be governed. This meter, through suitable control equipment, moves a pilot valve, which in turn controls the operating engine that opens or closes the wicket gates of the turbine. This paper describes the equipment and gives an account of progress to date, including experience with an experimental installation made on a 3,000-horsepower turbine operating under a head of 55 feet.

## Power Transmission and Distribution

**40-133—Superposition Methods in Calculating Effects of Additions to Power Systems;** *V. G. Rettig* (*A'32*). *10¢.* This paper outlines a group of methods that will permit calculation of all the common changes on power-system networks by superposition methods having as a basis the representation of loads as fixed currents. Investigation of the errors involved, and comparison with results obtained by assuming constant-impedance loads, when applied to the average power system networks in operation today, are included.

**40-107—Shielding of Transmission Lines;** *C. F. Wagner* (*M'37*), *G. D. McCann* (*A'38*), *and G. L. MacLane, Jr.* *10¢.* Modern theories of direct stroke protection premise that the ground wires are so located as to intercept the stroke and provide perfect shielding. In spite of the fundamental importance of this question there still exists considerable doubt as to the correct position of the ground wires relative to the transmission conductors. Two avenues of approach are suggested for the attack of this question; first, the collection of statistical information regarding actual line performance, and second, the use of laboratory models. Line performance is, after all, the final criterion. However, it is difficult to isolate the shielding effect from other factors which may produce outage due to lightning. Studies with models eliminate this difficulty but always contain the element of doubt as to whether the laboratory conditions are sufficiently representative of actuality as to justify general conclusions. Perhaps the best course, that which is attempted in this paper, is to try both and co-ordinate the results so obtained. (This paper also was presented at the 1940 AIEE summer convention, Swampscott, Mass., June 22–26.)

**40-126—Capacitors and Circuit Performance;** *J. W. Butler* (*M'38*). *10¢.* This paper analyzes the performance of circuits with different types of capacitor applications. By circuit performance is meant: voltage regulation, voltage level, voltage control, load division, power factor, and energy losses. These points are analyzed and discussed as they are influenced by both series and shunt capacitors. The field of application of capacitors, in distribution and transmission circuits, is fairly well indicated in this paper, so far as circuit performance is concerned. The economic picture obviously will have its influence in a specific solution, and the information offered herein should make it easier for one to evaluate the results he expects to obtain in the way of circuit performance from the installation of capacitors.

## Protective Devices

**40-134—A Double-Break Oil- or Gas-Blast Power Fuse;** *G. Leslie Hill* (*A'32*). *10¢.* The use of two use elements of different rating, in series, in a high-voltage fuse device is described in this paper. The two elements are placed in a tube and the tube is filled with an arc-extinguishing substance and sealed; one end with an expellable plug. In operation the lower rated element melts first on overcurrent and draws an arc; the energy from this arc is used to build up a pressure and forces the sealing plug out, which establishes a second arc. Then the pressure in the tube blasts the arc-extinguishing substance into the second arc and interrupts the circuit. Seven years' field experience has been obtained and is reported in this paper. The device has been applied on circuits up to 60 kv.

**40-114—The Vertical-Flow Interrupter and Its Application to Oil-Poor Circuit Breakers;** *B. P. Baker* (*A'38*). *10¢.* The historical background of the development of the vertical-flow interrupter for oil-poor circuit breakers is reviewed. A description of the interrupter and its theory of operation is given. The application of two of these interrupters to a 138-kv 1$^1/_2$-million-kva oil-poor porcelain-clad circuit breaker is shown, together with laboratory test results. A review is given of important field tests on a 138-kv single-pole unit, tested line to ground on a large 220-kv operating system up to approximately 2$^1/_4$ million three-phase kilovolt-amperes. Magnetic and cathode-ray oscillograms of these tests are shown.

**40-127—An Improved A-C Pilot Wire Relay;** *J. H. Neher* (*M'38*) *and A. J. McConnell* (*A'36*). *10¢.* This paper describes a relay system in which one standard relay element is used at each terminal. It is operative over a single telephone pair and gives full protection for any type of fault without the need for a potential supply. In addition, there is adequate insulation between the relay element and the pilot

wires. The relay is of the current-product type, in which the energy required to operate the element is provided largely by the polarizing current; thus permitting the use of a relatively low energy level in the pilot-wire circuit. In many respects this system is similar to the "Translay" system used successfully in Europe for many years. Of its several improvements, an outstanding one is the use of the modern high-speed induction-cylinder relay element.

**40-115—Displacement and Diffusion in Fluid-Flow Arc Extinction;** *Joseph Slepian* (*F'27*). *10¢*. The displacement and diffusion theories of arc extinction in flowing fluids are defined and contrasted. The question as to the possibility according to hydrodynamical principles of the formation of the wedge required by the displacement theory is considered and decided in the negative. Photographic evidence is also found to contradict the displacement theory. How turbulence will multiply diffusive effects is considered, and an estimate of 100-fold multiplication is given for conditions existing in gas-blast breakers. This enhancement of diffusion by turbulence is found to make the diffusion theory adequate for accounting for the circuit-interrupting capacities of arcs in gas-blast circuit breakers.

**40-129—Possibilities and Methods of Extending a Carrier-Current Relay Channel To Other Uses;** *R. M. Smith* (*A'35*) *and S. L. Goldsborough* (*A'24*). *10¢*. The authors point out some of the possibilities and requirements incidental to the use of carrier-current relay channels for such other supplementary services as telemetering, signaling, supervisory control, remote tripping, and communication. The conclusion is that definite economies can be effected by using a relay carrier channel for the purposes, particularly if the simultaneous performance of different services is not essential and that these additional uses sometimes justify the expense of the relay carrier-current installation. Simultaneous performance of different functions can be provided by the use of additional equipment.

# Personal • • •

**G. E. Edgerton** (M'29) colonel, Corps of Engineers, United States Army, has been appointed governor of the Panama Canal. He was born at Parkersville, Kans., April 17, 1887, received the degree of bachelor of science in mechanical engineering in 1904 and civil engineer in 1916 from Kansas State Agricultural College, and was graduated in 1908 from the United States Military Academy, in 1910 from the United States Army Engineering School, and in 1924 from the Army Command and General Staff School. He held the rank of lieutenant in the Corps of Engineers 1908–14; captain 1914–17; major 1917–31; lieutenant-colonel 1931–36; and colonel since 1936. He was an assistant engineer at the Panama Canal 1908–09; chief engineer, Alaska Road Commission, 1910–15; and from 1915 to 1919 was in the combat division of the Army in the Mexican expedition and the World War. During 1920–21 he was assistant to the chief of engineers, United States Army, in charge of supply and development of engineer equipment, and during 1921–23 was director of sales for the United States War Department. He went with the Federal Power Commission in 1924 as assistant chief engineer, and was chief engineer 1925–29. After a year as acting professor of civil military engineering at the United States Military Academy, West Point, N. Y., he became United States district engineer at Rock Island, Ill. He was made assistant to the chief of engineers, United States Army, in 1933, and in 1936 became engineer of maintenance at the Panama Canal. He is also a member of the American Society of Civil Engineers and other organizations.

**T. S. Sloan** (A'21, M'33) division manager of the Georgia Power Company at Columbus, Ga., and **L. M. Shadgett** (A'24, M'31) division manager at Athens, Ga., have been elected vice-presidents of the company, in accordance with a recent action of the board of directors by which all division managers were made vice-presidents. Mr. Sloan was born November 15, 1889, at Anderson, S. C., and attended Georgia School of Technology. He has been associated with the company and its predecessors since 1908 when he entered the operating department of the Georgia Railway and Power Company at Atlanta. In 1911 he went with the Central Georgia Power Company at Macon, and except for a year as superintendent of the Central Georgia Transmission Company, also at Macon, continued with that company until 1928. He was superintendent of substations 1913–23, and superintendent of operations 1923–28. He became division manager of the Georgia Power Company at Rome, Ga., in 1928, and was transferred to Columbus in 1937. Mr. Shadgett, a native (1899) of Adelaide, South Australia, graduated in mechanical and electrical engineering in 1921 from the South Australian School of Mines and Industries and the University of Adelaide. He was an engineer with the Adelaide Electrical Supply Company 1921–24, and from 1924 to 1928 was with the Alabama Power Company, Birmingham, as engineer and division superintendent. He has been with the Georgia Power Company since 1928, first as superintendent of wholesale operations and for the past three years as Athens division superintendent. He is a past chairman of the Georgia Section.

**H. S. Foley** (A'07, M'12) formerly vice-president and general manager of the Compania Colombiana de Electricidad, Barranquila, Colombia, has founded Motores Limitada, Bogota, Colombia, to distribute power machinery in Colombia for Westinghouse and other companies. Born January 21, 1884, at Kingman, Kans., he secured his technical training by correspondence courses. In 1900 he entered the employ of the Mexican Central Railroad Company as assistant electrician, and in 1904 went with the Mexican Light and Power Company, Mexico City, as foreman on transmission line construction, later becoming superintendent. He continued in Mexico until 1914, during the last four years serving also as superintendent of overhead trolley construction for Mexican Trainways Company. From 1914 to 1916 he was superintendent of distribution for the Ebro Irrigation and Power Company, Barcelona, Spain, and in 1916 became purchasing engineer in New York, N. Y., for the Compagnie Générale d'Électricité, Paris, France. Four years later he was appointed chief engineer of the Compania Hidroelectrica é Irrigadora del Chapala, Guadalajara, Mexico, and several years later became general manager of the Empressa Electrica del Ecuador, Inc., Guayaquil, Ecuador, of which he was subsequently appointed vice-president. He had been vice-president and general manager of the Colombia company since 1929.

**M. F. Gill** (A'14, M'33) has been elected president and general manager of the Kansas Gas and Electric Company, Wichita. Born at Paris, Tex., October 4, 1888, he received the degree of electrical engineer at the University of Texas in 1910. He was a student engineer with the General Electric Company, Schenectady, N. Y., 1910–12, returning to Texas in 1913 as resident engineer for the Texas Power and Light Company, Dallas. He continued with the company until 1917, becoming office engineer, and assistant chief engineer. After brief periods with the Stone and Webster Engineering Corporation, the United States Army, and the Phoenix Utility Company, he became assistant manager in 1919, and later manager, of the Texas Electric Service Company, Brackenridge and Eastland. He continued as manager, having charge of utility operation, engineering, and construction, until 1928, when he became general superintendent of the Phoenix Utility Company at Allentown, Pa. In 1935 he became co-ordinator for the Pennsylvania Power and Light Company, at Allentown, and in 1937 went to Kansas Gas and Electric as assistant to the president.

**C. E. Ide** (A'16, M'38) has been elected president of the East Tennessee Light and Power Company, Bristol, Tenn. He was born February 4, 1892, at Brayton, Iowa, and received the degree of bachelor of science in electrical engineering from Iowa State College in 1914. He has been associated with utility properties in the Cities Service system ever since, having been with the Denver (Colo.) Gas and Electric Light Company 1914–15; the Toledo (Ohio) Railways and Light Company 1915–16; statistical engineer in the New York, N. Y., office of Henry L. Doherty and Company, 1916–17; and with the Meridian (Miss.) Light and Railway Company, 1917–18. During the World War he was a member of the science and research division of the Signal Corps of the United States Army, returning to Henry L. Doherty and Company for the next eight years. He became vice-president and general manager of the East Tennessee Light and Power Company in 1927, and the following year assumed the same positions with the Tennessee Eastern Electric Company, Bristol. He was president of the Southeastern Electric Exchange 1939–40.

**T. G. Miller** (A'16) retired July 1, 1940, as vice-president in charge of the long-lines department of the American Telephone and Telegraph Company, New York, N. Y. Born June 22, 1880, at Sandusky, Ohio, he studied mechanical engineering at Massachusetts Institute of Technology. After leaving college because of illness, he was employed by the Lunkenheimer Company, Cincinnati, Ohio, for a time and later spent several years in railroad work in the Southwestern United States and Mexico. He entered the long-lines department of the American Telephone and Telegraph Company in New York in 1904, and in 1906 was made district supervisor of line maintenance at Atlanta, Ga. He returned to New York in 1907 and held various positions in the general office until 1913. From 1913 to 1919 he was division plant superintendent at Chicago, Ill., returning to New York as acting general plant superintendent. He became general plant manager in 1920, general manager in 1924, and vice-president in charge of the department in 1930.

**C. L. Proctor** (A'08) has been elected president of the Toledo (Ohio) Edison Company. Born in Charlotte County, Va., February 3, 1880, he received the degrees of bachelor of science in 1902 and mechanical engineer in 1903 from Virginia Military Institute. Following graduation he entered the test course of the General Electric Company at Schenectady, N. Y., and two years later was transferred to the railway department. He became general superintendent of the Athens (Ga.) Railway and Electric Company in 1908, continuing until 1915, when he became sales manager of the Empire District Electric Company, Joplin, Mo. He was vice-president and general manager of the Danbury and Bethel Gas and Electric Light Company, Danbury, Conn., 1918–19, returning to the Empire District company in that capacity in 1919. He went to Toledo Edison in 1925 as vice-president and general manager, continuing in that position until his present appointment. He was made a director of Cities Service Power and Light Company in 1939.

**C. F. Craig** (M'27) general manager, long-lines department, American Telephone and Telegraph Company, New York, N. Y., has been elected vice-president in charge of the department. Born April 6, 1893, at Rich Hill, Mo., he received the degree of bachelor of science in electrical engineering from the University of Missouri in 1913. The same year he entered the employ of the American Telephone and Telegraph Company at St. Louis, Mo., as an equipment attendant. He was engaged in cost studies and outside plant engineering there and at Kansas City until 1918, when he was made district plant chief (later superintendent) at St. Louis. In 1922 he was transferred to New York, N. Y., as plant accountant, becoming construction supervisor in 1923. He was sent to Atlanta, Ga., in 1925 as division plant superintendent, returning to New York in 1927 as special representative in the general department. He was made general manager of the long-lines department in 1933.

**L. O. Ripley** (A'05) has retired as president of the Kansas Gas and Electric Company, Wichita, but will continue with the company as director in a consulting capacity. Born April 20, 1877, at Laurens, N. Y., he was graduated from Union College in electrical engineering in 1900. After graduation he was employed by the Clark Estates and by the Clinton Mills Power Company, both at Cooperstown, N. Y., and as superintendent of construction of the municipal power plant at Marathon, N. Y. In 1903 he became superintendent of the light and power department of the Schenectady (N. Y.) Railway Company, and when the Schenectady Illuminating Company was separated from the railway company in 1905 he became manager of the latter. He went to Wichita when the Kansas Gas and Electric Company was organized, in 1909, as vice-president, and has been chief operating executive ever since.

**W. E. Groves** (A'37) has been awarded the AIEE District 9 prize for Branch paper for 1939 jointly with Opal Cummins for their paper "Water-Cooled Radio-Frequency Amplifier With Grounded Anodes". The paper also received the award of the Utah Section for 1939. A native (1907) of Fort Worth, Tex., he received the degree of bachelor of arts from the University of Utah in 1936, and was carrying on further study there at the time the paper was written. He was a radio net operator for the United States War Department 1927–29 and is a graduate of the Army Signal School. Since 1929, except for a short period as chief engineer of station KLO, Ogden, Utah, he has been employed by station KSL, Salt Lake City, Utah, of which he is now chief engineer. He is also a member of the Institute of Radio Engineers.

**G. H. Calkins** (A'07, M'29) retired July 1, 1940, as manager of the Buffalo, N. Y., office of the General Electric Company. Born September 29, 1873, at New England, Ohio, he received the degree of electrical engineer in mechanical engineering from Ohio State University in 1895. He was a fellow and instructor in the department of physics at Ohio State, Columbus, 1895–96, and was also engaged in railway construction for the Degnon Construction Company, Columbus, and in consulting engineering, before going with General Electric in 1899. He was at Schenectady, N. Y., in the test course, and production and sales departments until 1906, when he became manager of the New Haven office of the company. Since 1907 he has been manager of the Buffalo office.

**Nejat Atsan** (A'40) has received the AIEE District 7 prize for graduate paper for 1939 for his paper "A Method of Line-Voltage Control". Born February 23, 1905, at Istanbul, Turkey, he studied marine engineering at the Turkish Naval Academy, and received the degree of bachelor of science from the Ingenieur Academie, Oldenburg, Germany, in 1930, and that of master of science in electrical engineering from the University of Missouri in 1939. He served as a first lieutenant in the Turkish war fleet from 1930 to 1934, and was a wireless engineer 1934–37 for the Turkish Ministry of Communication at Ankara, Turkey, for which he is now an electrical and wireless engineer. He is also a member of the Verein Deutscher Elektrotechniker.

**T. E. Curtis** (A'40) has received the AIEE District 8 prize for Branch paper for 1939 for his paper "Compound Frequency Control of Power Systems". Born June 26, 1917, at Long Beach, Calif., he received the degree of bachelor of science in electrical engineering from the University of California in 1939. Since graduation he has been employed as electric underground estimator by the Pacific Gas and Electric Company, at Oakland, Calif. He received the award of the San Francisco Section in 1939 for prize-winning paper presented at a joint meeting of Branches in that Section. He is also a member of Sigma Xi, Tau Beta Pi, and Eta Kappa Nu.

**J. W. McNall** (A'38) research engineer in the lamp division of the Westinghouse Electric and Manufacturing Company at Bloomfield, N. J., has been awarded the B. G. Lamme graduate scholarship for 1940–41. He will study electronic physics. Born October 19, 1914, at Cleveland, Ohio, he received the degree of bachelor of science from Case School of Applied Science in 1936, and has done some graduate work at the University of Pittsburgh. Following his graduation he entered the research laboratories of the Westinghouse company at East Pittsburgh, and in 1938 was transferred to the lamp division. He is a member of Tau Beta Pi and Sigma Xi.

**Wills Maclachlan** (A'08, F'21) consulting engineer, Toronto, Ont., Can., has been elected president of the Royal Canadian Institute. He has been particularly concerned with accident prevention and industrial relations in his consulting practice, serving the Electrical Employers Association of Ontario, Hydroelectric Power Commission of Ontario, Toronto Hydroelectric System, and other public and private organizations. He has been chairman of the AIEE committee on safety since 1937, was a vice-president (1919–20), and has been active on other committees of the AIEE and in other organizations in the United States and Canada.

**W. D. Howell** (A'38) industrial power engineer, Pacific Gas and Electric Company, San Francisco, Calif., has been awarded an Alfred P. Sloan Foundation fellowship for a year's graduate study in the graduate school of business administration, Massachusetts Institute of Technology, Cambridge. He has been given leave of absence from Pacific Gas and Electric for that period. Mr. Howell, who received the degree of bachelor of science from the University of California in 1932, was recently transferred to San Francisco after being with the East Bay sales office of Pacific Gas and Electric at Oakland, Calif., since 1926.

**V. G. Rettig** (A'32) electrical engineer, Cincinnati Gas and Electric Company, Cincinnati, Ohio, has been awarded first prize in the James H. McGraw prizes of the

Edison Electric Institute for the three most meritorious papers on engineering or technical subjects related to the electrical industry, for his paper entitled "Basis for a Program of Capacitor Additions on a Growing Distribution System". Mr. Rettig, who received the degree of electrical engineer at the University of Cincinnati in 1930, has been with the Cincinnati utility in various capacities since 1928. He is a member of Eta Kappa Nu and Tau Beta Pi.

**D. S. Snell** (A'24) electrical engineer, a-c turbine engineering department, General Electric Company, Schenectady, N. Y., has been awarded AIEE District 1 prize for best paper for 1939 for his paper "The Hydrogen-Cooled Turbine Generator". Mr. Snell who holds the degrees of bachelor of science (1919) and master of science (1921) in electrical engineering from Union College, Schenectady, N. Y., was an instructor there 1921–22. He had previously spent 18 months in the testing department of General Electric, and since 1922 has been with that company continuously.

**H. D. Green** (M'35) with J. J. Joy and F. P. Kuhl received the cash prize accompanying the Augustus D. Curtis award of the Edison Electric Institute. The award, which is for contributions to the advancement of artificial illumination of public or commercial buildings, was presented in 1940 to the Consolidated Edison Company of New York, Inc., New York, N. Y., for a relighting installation in its mechanical engineering drafting room (*see EE, Feb. '40, p. 68–9*). Mr. Green, an assistant division engineer for the company, was honored as one of the individuals responsible for the achievement.

**H. R. Sills** (A'24, M'31) has received the AIEE District 10 prize for best paper for 1939 for his paper "Vertical Shaft Generators" (*EE, Dec. '39, p. 469–79*). A native (1900) of Kingston, Ont., Can., he received the degree of bachelor of science from Queens University in 1921. Following graduation he entered the test course of the Canadian General Electric Company, Ltd., at Peterboro, Ont., and since 1925 has been assistant engineer in charge of design of large generators and special machines. He received the District 10 prize for initial paper in 1928.

**A. M. Doyle** (A'37) has received the AIEE District 10 prize for initial paper for 1939 for his paper "Lightning Protection for Power Transmission Systems". Born June 15, 1908, at Winnipeg, Man., Can., he received the degree of bachelor of science in electrical engineering from the University of Manitoba in 1928. He entered the employ of the Canadian General Electric Company, Ltd., as a student in the test course, was later transferred to the transformer design department, and since 1930 has been a transformer sales engineer in the Toronto office of the company.

**Opal Y. Cummins** (membership application pending) has been awarded the AIEE District 9 prize for Branch paper for 1939 jointly with W. E. Groves for their paper "Water-Cooled Radio-Frequency Amplifier With Grounded Anodes". The paper also received the 1939 award of the Utah Section. Born at Salt Lake City, Utah, September 2, 1919, Miss Cummins received the degree of bachelor of science in electrical engineering from the University of Utah in 1939, and is at present employed as a draftsman by the International Smelting and Refining Company, Salt Lake City.

**A. E. Harrison** (A'39) has received the AIEE District 8 prize for graduate paper for 1939 for his paper "Ionization Time of Thyratrons". A native (1908) of San Luis Obispo, Calif., he received the degree of bachelor of science from the University of California in 1936 and that of master of science from California Institute of Technology in 1937. He was a teaching fellow at the latter institution 1937–39, and is at present employed by the Sperry Gyroscope Company, San Carlos, Calif.

**H. N. Steen** (A'31) has received the AIEE District 9 prizes for best paper and initial paper for 1939 for his paper "A Three-Element Cathode-Ray Oscillograph". A native (1906) of Seattle, Wash., he received the degree of bachelor of science in electrical engineering from the University of Washington. He has been employed as a laboratory assistant at the University of Washington, Seattle; as assistant engineer by the Seattle Cedar Lumber Manufacturing Company; and is at present engineer for the Instrument Laboratory, Inc., Seattle.

**W. M. Goodhue** (A'31) has received honorable mention in the AIEE District 1 prize for best paper for 1939 for his paper "The Rectifier Calculus". Mr. Goodhue, who received the degrees of bachelor of science (1928) and master of science (1929) from Harvard University, has been associated with the department of electrical engineering there since 1929, first as assistant and then as instructor.

**P. J. Reifschneider** (Enrolled Student) has received the AIEE District 3 prize for Branch paper for 1939 for his paper "An Electronic Voltage Regulator for an Alternator". Born in Brooklyn, N. Y., September 30, 1917, he received the degree of bachelor of electrical engineering from the Polytechnic Institute of Brooklyn in 1939, and is at present studying for his master's degree at the same institution.

**Conrad Creim** (A'34) has been appointed chief electrical and mechanical engineer for Jahn-Bressi-Bevanda Constructors, Inc., Los Angeles, Calif., on the Tucumcari tunnel project at Conchas Dam, New Mexico. Since graduation from the University of California in 1933 he had been in the employ of the Los Angeles Metropolitan Water District.

**Robert B. Bonney** (Enrolled Student) has received the AIEE District 7 prize for Branch paper for 1939 for his paper "Directional Antennas for Broadcast Stations". A native of Cimarron, N. Mex., he was at that time a student in electrical engineering at the University of New Mexico.

**C. S. Cole** (A'30, M'35) has been transferred from the Buffalo Niagara Electric Corporation, Niagara Falls, N. Y., to the Niagara Lockport and Ontario Power Company at Medina, N. Y. He has been employed by operating companies of the Niagara Hudson System since 1934, in charge of changeover programs in western New York State in connection with the change in frequency from 25 to 60 cycles.

**C. E. Boulson** (A'40) has been employed by the Missouri Electric Power Company, Marshfield, as electrical engineer in charge of distribution load studies. Since graduating from the Missouri School of Mines in 1939 he had been with Jay Samuel Hartt, Madison, Wis., on inventory work connecting with setting up a uniform system of accounts for Missouri Electric.

**Paul Lebenbaum, Jr.** (A'37) formerly supervisor of the electrical engineering section of the General Electric Company's advanced course in engineering, at Schenectady, N. Y., has been transferred to the motor engineering department of the company, at Lynn, Mass.

**E. R. Stauffacher** (A'15, M'26) has been transferred from the power engineering division of the commercial department of the Southern California Edison Company, Ltd., Los Angeles, Calif., to general engineering work in the operating department, with the title of electrical engineer.

**R. A. Fuller** (A'29) formerly in the commercial refrigeration department of the General Electric Company, Fort Wayne, Ind., has been appointed application engineer in commercial refrigeration and air conditioning, with headquarters at the company's River Works, West Lynn, Mass.

**R. M. Darrin** (A'28, M'34) formerly in charge of central-station sales for the Buffalo office of the General Electric Company, has been made manager of the Syracuse office. He has been with the company since 1919.

**G. B. Hoadley** (A'35) formerly instructor in electrical engineering, Massachusetts Institute of Technology, Cambridge, has been appointed assistant professor of electrical engineering, Polytechnic Institute of Brooklyn, N. Y.

**E. F. King** (A'37) formerly engineer in the radiant-heat division, C. M. Hall Lamp Company, Detroit, Mich., has become an instructor in electricity and radio at the Boeing School of Aeronautics, Oakland, Calif.

**P. L. Bellaschi** (A'29, F'40) section engineer, transformer engineering department, Westinghouse Electric and Manufacturing Company, Sharon, Pa., recently was awarded the honorary degree of doctor of science by Washington and Jefferson College.

**W. G. Robertson** (A'24, M'38) formerly assistant valuation engineer, State Corporation Commission of Virginia, Richmond, is now electrical engineer for the Clifton Forge Waynesboro (Va.) Telephone Company.

**L. G. Snyder** (A'23, M'35) formerly sales manager, Landis and Gyr, New York, N. Y., is now sales manager in charge of central station sales, Metropolitan Device Corporation, Brooklyn, N. Y.

**C. E. Creccy** (A'15, M'27) formerly plant extensions engineer, Chesapeake and Potomac Telephone Company of Virginia, Richmond, has been appointed transmission and outside plant engineer.

**F. A. Rechif** (A'38) formerly assistant operator, geophysical department, Continental Oil Company, Ponca City, Okla., is now employed as engineer by the Mott-Smith Corporation, Houston, Tex.

**S. P. Shelton** (A'37) formerly with the City of Los Angeles (Calif.) Department of Water and Power, is now with the Public Works Division of the Puget Sound Navy Yard, Bremerton, Wash.

**G. E. Hulse** (M'22) chief engineer, the Safety Car Heating and Lighting Company, New Haven, Conn., has been nominated a manager of the American Society of Mechanical Engineers for 1941.

**E. J. Barrett** (A'39) formerly serviceman, Sierra Pacific Power Company, Reno, Nev., has been made draftsman in the engineering department of the company.

# Obituary

**Jacques W. Wegrin** (A'29) consulting engineer, New York, N. Y., died November 26, 1939, according to information just received at Institute headquarters. He was born December 25, 1883, at Kreutzburg, then in Russia, and received his technical training at the College of Engineering, Cothen, Germany. He also studied at the University of California. He was an electrical engineer for H. Rouland Company, Berlin, Germany, 1905–06, and superintendent of a power plant and mountain railway at Dresden, Germany, 1907–08. In 1908 he organized a power and light company at Riga, Russia, which he continued to manage until 1912, also handling Russian sales for two German equipment companies. From 1912 to 1915 he was sales engineer in Russia for Landis and Gyr, Switzerland. After coming to the United States he wrote for German and Russian trade magazines, and beginning in 1922 was associated as consulting engineer with various Russian trade organizations, including the Amtorg Trading Corporation.

**David Ittin** (A'30) shift engineer, Haifa Power Station, Palestine Electric Corporation, Ltd., Haifa, Palestine, died August 21, 1939, according to information just received at Institute headquarters. He was born December 29, 1906, at what is now Stalingrad, USSR, and received the degree of bachelor of science in electrical engineering at Armour Institute of Technology in 1928. After a year in the test course at General Electric Company, Schenectady, N. Y., he was transferred to the commercial engineering department of International General Electric Company. He was later employed for several years as inspector for the Brooklyn (N. Y.) Edison Company, before going to Haifa as engineer for the Palestine Electric Corporation.

**Harry William Motter** (A'18, M'31) sales and consulting engineer, York, Pa., died May 30, 1940. He was born October 14, 1889, at York, Pa., and was graduated in electrical engineering at Lehigh University in 1913. From 1913 to 1919 he was engaged as electrical engineer in charge of the electrical department of George F. Motter's Sons, York. In 1919 he organized his own business as sales and consulting engineer, serving industrial and utility companies, and acting as district representative for various electrical manufacturing firms. He continued in this practice until his death.

**Gerald C. Young** (A'37) engineer, Abington Electric Company, Clarks Summit, Pa., died June 23, 1940. He was born May 28, 1904, at Cumberland, Md., and received the degree of bachelor of science in electrical engineering from Virginia Polytechnic Institute in 1926. Following graduation he entered the cadet engineering course of the Chester Valley Electric Company, Coatesville, Pa. He had been with the Abington Electric Company since 1928. He was also a member of the Pennsylvania Electric Association.

**Ralph Maynard Towne** (A'36) consulting engineer, Tacoma, Wash., died May 24, 1940. He was born April 1, 1912, at Salt Lake City, Utah, and received the degree of bachelor of science in electrical engineering from the University of Washington in 1935. He had been engaged in design and construction of utility plants and lines and in REA construction work since his graduation. He was also a member of Tau Beta Pi and Sigma Xi.

# Membership

## Recommended for Transfer

The board of examiners, at its meeting on July 25, 1940, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

**To Grade of Member**

Appleby, H. A., assistant signal engineer, Atchison, Topeka and Santa Fe Railway Company, Amarillo, Tex.
Collens, C. L., president, Reliance Electric and Engineering Company, Cleveland, Ohio.
Craig, H. M., field engineer, Bell Telephone Laboratories, Chicago, Ill.
DuMont, P. J., assistant port engineer, Grace Lines, Inc., New York, N. Y.
Dyer, J. M., transmission engineer, Southwestern Light and Power Company, Lawton, Okla.
Loewe, Robert, electrical engineer, Commonwealth and Southern Corporation, Jackson, Mich.
Murdock, H. B., division superintendent, Montana Power Company, Bozeman
Paxton, Robert, managing engineer, General Electric Company, Philadelphia, Pa.
Pearce, C. T., Middle Atlantic engineering manager, Westinghouse Electric and Manufacturing Company, Philadelphia, Pa.
Picksley, Wm. M., assistant engineer, Allis-Chalmers Manufacturing Company, Milwaukee, Wis.
Potter, E. A., member of technical staff, Bell Telephone Laboratories, New York, N. Y.
Rick, G. D., assistant power supervisor, Public Service Company of Northern Illinois, Wheaton, Ill.
Stanley, F. L., plant extension engineer, Indiana Bell Telephone Company, Indianapolis, Ind.
Straus, F. N., electrical and mechanical engineer, Austin Company, Cleveland, Ohio.
Troxel, F. D., electrical engineer, Sargent and Lundy, Inc., Chicago, Ill.
Worth, D. G., associate electrical engineer, Bonneville Power Administration, Portland, Ore.
Zane, R. B., electrical engineer, The Okonite Company, Chicago, Ill.

17 to Grade of Member

## Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Names of applicants in the United States and Canada are arranged by geographical Districts. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before August 31, 1940, or October 31, 1940, if the applicant resides outside of the United States or Canada.

**United States and Canada**

1. NORTH EASTERN

Herman, W. P. (Member), Electrix Corporation, Pawtucket, R. I.
Nims, P. T., American Bosch Corporation, Springfield, Mass.

2. MIDDLE EASTERN

Brown, C. E., Jr., The Okonite Company, Washington, D. C.
Johnson, P. S. (Member), Union Switch and Signal Company, Swissvale, Pa.
Muhovich, M. R., Westinghouse Electric and Manufacturing Company, Sharon, Pa.

3. NEW YORK CITY

Marculescu, G. B., 728 West 181 Street, New York, N. Y.
Martianov, V., Amtorg Trading Corporation, New York, N. Y.
Truckess, D. E. (Member), Bell Telephone Laboratories, New York, N. Y.

4. SOUTHERN

Bedford, E. M., Jr., Commonwealth and Southern Corporation, Birmingham, Ala.
Cahoon, W. H. (Member), Tennessee Valley Authority, Knoxville, Tenn.
Slater, H. A., Tennessee Valley Authority, Chattanooga, Tenn.
Taylor, E. T., Tennessee Valley Authority, Wilson Dam, Ala.
Wood, B. T., Mathieson Alkali Works, Inc., Lake Charles, La.

5. GREAT LAKES

Bailey, T. G., Commonwealth Edison Company, Chicago, Ill.
Bernthal, V. O., Public Service Company of Northern Illinois, Joliet, Ill.
Browell, E. G., Illinois Valley Electric Co-operative, Princeton, Ill.
Grinstead, C. E., General Motors Research Laboratories, Detroit, Mich.
Riche, L. L. (Member), Micro Switch Corporation, Freeport, Ill.

6. NORTH CENTRAL

Tilden, W. C., Loup River Public Power District, Columbus, Nebr.

7. SOUTH WEST

Rausbenberger, E. J., A. Y. Taylor and Company, Clayton, Mo.
Robb, J. D., Geiger's Plumbing and Electrical Shop, Boonville, Mo.

9. NORTH WEST

Cummins, O. Y., International Smelting and Refining Company, Salt Lake City, Utah.
Rorberg, C. E., Washington Water Power Company, Spokane.

10. CANADA

Taylor, K. D., Hydro Electric Power Commission of Ontario, Simcoe.
Wighton, J. J., Canadian Broadcasting Corporation, Vancouver, B. C.

Total, United States and Canada, 25

**Elsewhere**

Capwell, G. L. (Member), Empresa Electrica Del Ecuador, Inc., Guayaquil, Ecuador.
Clifford, A. E. (Member), Harland Engineering Company, Alloa, Scotland.
Han, Y. K., Yoon Radio Service, Penang, Straits Settlements.
Teal, A. E. (Member), Public Works Department, Gurdaspur, Punjab, India.
Venkataraman, M. K. R., care of Imperial Bank of India, London, E.C. 2, England.

Total, elsewhere, 5

# Transactions

**Preprint of Technical Papers Comprising Pages 417–88 of the 1940 Volume**


## Lightning Currents in Arresters at Stations


I. W. GROSS
MEMBER AIEE

W. A. McMORRIS
MEMBER AIEE


A CO-OPERATIVE field investigation of the lightning currents discharged by arresters at stations was undertaken in 1936, by the engineering departments of the American Gas and Electric Service Corporation and the General Electric Company. Data have previously been published on the currents discharged by distribution lightning arresters[1,2,3] but little information is available on the duty required of arresters located in stations, where considerable influence on incoming lightning waves may be produced by a large number of circuits connected to one bus, by the capacitance to grounded steel work in the station, by the more or less sheltered location of some stations, and by types of construction commonly used for transmission lines.

The data so far obtained show that there are large variations in the number of arrester discharges from season to season, and that due to local conditions the duty on arresters is far more severe in some locations than others, making it difficult to arrive at a representative average. Hence the investigation is to be continued in order that the effects of these factors may be better determined. Some redistribution of field installations may be made to provide more information on points where the data have been meager.


Paper 40-59, recommended by the AIEE committee on protective devices, and presented at the AIEE winter convention, New York, N. Y., January 22–26, 1940. Manuscript submitted November 24, 1939; made available for preprinting January 3, 1940; released for final publication February 28, 1940.



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A large number of people in several organizations have contributed to make an investigation of this type possible and to correlate the data in suitable form for presentation. The authors wish to express their appreciation to the Ohio Power Company, the Appalachian Electric Power Company, the Atlantic City Electric Company, and the Indiana and Michigan Electric Company, where the field work was done; and to those in the Engineering Departments of the General Electric Company and the American Gas and Electric Service Corporation who supervised the work and analyzed the records. Acknowledgment is made to the helpful assistance of George D. Lippert of the American Gas and Electric Service Corporation for correlating the records on which the paper is based, and to Doctor K. B. McEachron and D. D. MacCarthy of the General Electric Company for their assistance in organizing and directing the progress of the investigation.


1. For all numbered references, see list at end of paper.

### Scope and Conduct of Investigation

In this investigation the field work was carried on for four years (1936–1939) on four American Gas and Electric Company properties; the Ohio Power Company in Ohio, the Appalachian Electric Power Company in Virginia, the Atlantic City Electric Company in New Jersey, and the Indiana and Michigan Electric Company in Indiana. This diversified territory provided an opportunity for studying lightning conditions as affecting arresters, on properties employing different practices, and with isokeraunic levels varying from 27 to 45 thunderstorm days per year.

**Figure 1. Wooden bracket supporting two surge-crest-ammeter links on lead to lightning arrester**

Measurements of arrester discharge currents were made with surge-crest-ammeter links[4] mounted on each leg of each three-pole arrester, in a straight part of the conductor between the arrester and the line. Typical field installations are shown in figures 1, 2, and 3. Links were serviced approximately every two weeks during the lightning season for four years, and any which indicated that current had passed through the arrester were removed for calibration and replaced with demagnetized links. The magnetized links were checked in the field in some cases, but received a final calibration at the Pittsfield works of the General Electric Company.

The current measuring installations are listed in table I, where they are grouped

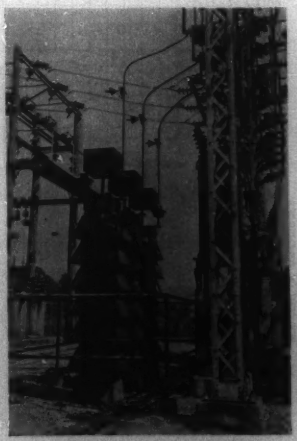

**Figure 2. Surge-crest-ammeter link installations on all three poles of 33-kv oxide-film lightning arrester**

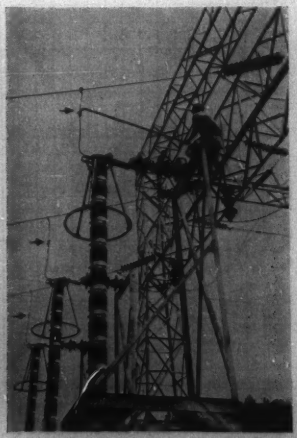

**Figure 3. Field servicing of surge-crest-ammeter links on Thyrite lightning arrester on 132-kv energized circuit**

according to several different classifications. The installations were confined to arresters in stations only, and included arresters connected to lines where they entered the stations, arresters on or immediately adjacent to power transformers, and arresters connected to station busses. The arresters were of several different designs. Approximately 75 per cent were designated by the manufacturer as "station type" and 25 per cent as "line type". All circuits involved operated with grounded neutrals, at line-to-line voltage ratings of 11 to 132 kv.

One hundred three-pole arresters were equipped in 1936 for the measurement of lightning discharge currents. This number was increased each year until 1939, when 166 were under investigation. The total three-pole arrester-years for the four-year period was 580*, making an average of 145 under study each year. On the basis of single-pole arresters, the study included 1,734 arrester-years, or an average of 433.5 each year.

## Number of Records Obtained

A total of 459 records of lightning currents discharged by single-pole arresters were obtained during the four-year period, or 0.79 records per three-pole arrester per year. The maximum number of single-pole records obtained during the four-year period on any one three-pole arrester was 29, and three other arresters yielded 24 records each.

**Table I. Number of Three-Pole Lightning Arresters Equipped With Surge-Crest-Ammeter Links, 1936 to 1939 Inclusive**

| Type of Arresters or Connected Transmission Lines | Number of Three-Pole Arresters Equipped With Surge-Crest-Ammeter Links | | | | |
|---|---|---|---|---|---|
| | 1936 | 1937 | 1938 | 1939 | Total |
| Arrester *A* | 5 | 0 | 0 | 0 | 5 |
| Arrester *B* | 2 | 5 | 5 | 5 | 17 |
| Arrester *C* | 62 | 105 | 105 | 105 | 377 |
| Arrester *D* | 26 | 30 | 29 | 27 | 112 |
| Arrester *E* | 5 | 12 | 23* | 29** | 69** |
| Total | 100 | 152 | 162* | 166** | 580** |
| Station-type arresters | 74 | 122 | 122 | 122 | 440 |
| Line-type arresters | 26 | 30 | 40* | 44** | 140** |
| Total | 100 | 152 | 162* | 166** | 580** |
| Arresters connected to: | | | | | |
| 11-kv lines | 0 | 2 | 2 | 2 | 6 |
| 22-kv lines | 17 | 30 | 33 | 32 | 112 |
| 27-kv lines | 0 | 23 | 25* | 31** | 79** |
| 33-kv lines | 46 | 46 | 48 | 47 | 187 |
| 44-kv lines | 1 | 1 | 1 | 1 | 4 |
| 66-kv lines | 1 | 11 | 13 | 13 | 38 |
| 88-kv lines | 1 | 1 | 1 | 1 | 4 |
| 132-kv lines | 34 | 38 | 39 | 39 | 150 |
| Total | 100 | 152 | 162* | 166** | 580** |
| Arresters connected to: | | | | | |
| Wood-pole lines | | | | | |
| No ground wire | 14 | 30 | 32 | 31 | 107 |
| One ground wire | 30 | 46 | 53* | 58** | 187** |
| Steel-tower lines | | | | | |
| No ground wire | 5 | 9 | 9 | 9 | 32 |
| One ground wire | 38 | 43 | 44 | 44 | 169 |
| Two ground wires | 2 | 7 | 7 | 7 | 23 |
| Mixed circuits | 11 | 17 | 17 | 17 | 62 |
| Total | 100 | 152 | 162* | 166** | 580** |

* Includes one two-pole arrester installation. ** Includes five two-pole arrester installations.

Table II summarizes the number of records per arrester for the 85 three-pole arresters that remained in service during the entire four-year period. These were all on Ohio Power Company and Appalachian Electric Power Company circuits, where the severity was above the average for the four operating companies.

**Table II. Number of Records Per Arrester During Four-Year Period, 1936–39**

Based on 344 Records From 85 Three-Pole Arresters Which Remained in Service During the Entire Four-Year Period, all on Ohio Power Company and Appalachian Electric Power Company Circuits

| Number of Single-Pole Records Per Arrester | Number of Arresters | Per Cent of Total Arresters |
|---|---|---|
| 0 | 27 | 31.7 |
| 1 | 17 | 20.0 |
| 2 | 9 | 10.6 |
| 3 | 1 | 1.2 |
| 4 | 7 | 8.2 |
| 5 | 7 | 8.2 |
| 7 | 3 | 3.5 |
| 8 | 2 | 2.4 |
| 9 | 1 | 1.2 |
| 10 | 1 | 1.2 |
| 11 | 1 | 1.2 |
| 12 | 2 | 2.4 |
| 14 | 1 | 1.2 |
| 17 | 1 | 1.2 |
| 20 | 1 | 1.2 |
| 24 | 3 | 3.5 |
| 29 | 1 | 1.2 |
| Total | 85 | 100 |

* Including six installation-years on two-pole arresters.

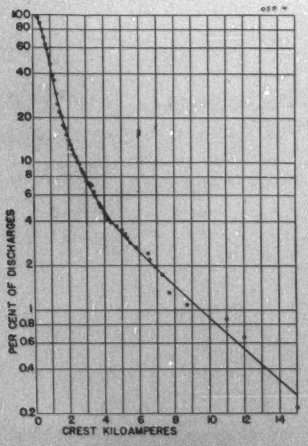


**Figure 4. Current magnitude of recorded arrester discharges**

Curve shows per cent of discharges with current magnitude at least as great as indicated

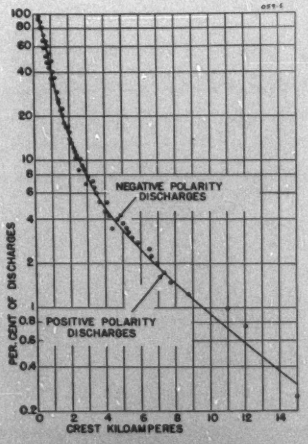


**Figure 5. Comparison between magnitudes of positive and negative polarity discharges**

Curve shows per cent of discharges with current magnitude at least as great as indicated

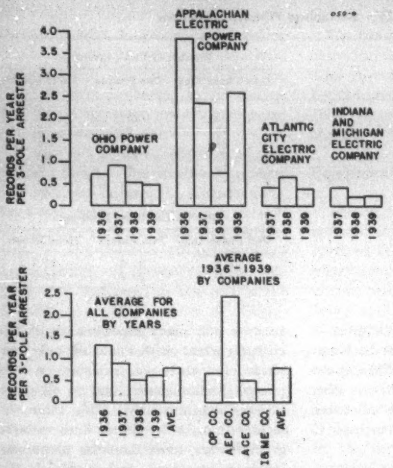
RECORDS PER YEAR PER 3-POLE ARRESTER
OHIO POWER COMPANY
APPALACHIAN ELECTRIC POWER COMPANY
ATLANTIC CITY ELECTRIC COMPANY
INDIANA AND MICHIGAN ELECTRIC COMPANY
1936 1937 1938 1939
AVERAGE 1936 - 1939 BY COMPANIES
AVERAGE FOR ALL COMPANIES BY YEARS
1936 1937 1938 1939 AVE.
OP CO. AEP CO. ACE CO. I&M E CO. AVE.

**Figure 6 (left). Variation in number of records obtained from year to year, and between different localities**

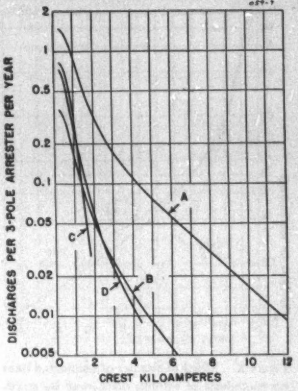


**Figure 7 (right). Effect of line construction on number and magnitude of arrester discharge currents**

Curves show number of discharges per three-pole arrester per year which have current magnitudes at least as great as indicated

*A*—Wood-pole lines without ground wires

*B*—Wood-pole lines with ground wires

*C*—Steel-tower lines without ground wires

*D*—Steel-tower lines with ground wires

## Magnitude of Currents

The highest individual arrester discharge current recorded was 15,000 amperes, and 16 measurements or 3.5 per cent of the total were 5,000 amperes or more. Arresters at certain locations were subjected repeatedly to high discharge currents.

In many cases there were several arresters in one station connected so that they could operate in parallel. The current which any one might have been called upon to discharge, in the absence of the others, may be estimated by adding together the currents recorded simultaneously in all of the arresters. The highest value obtained in this way for any one phase is 19,000 amperes.

The current measurements obtained are summarized in table III, where the maximum, minimum, and the median current (the current exceeded in 50 per cent of the cases) are listed for several operating conditions, together with the number of current measurements and arrester installation-years upon which the values are based. Figure 4 shows how the 459 current records were distributed with regard to magnitude.

**Table III. Summary of Recorded Arrester Discharge Currents, 1936 to 1939 Inclusive**

| Type of Arresters or Connected Circuits | Number of Three-Pole Arrester-Years | Number of Single-Pole Discharges Recorded | Values of Discharge Currents in Amperes | | |
|---|---|---|---|---|---|
| | | | Max. | Min. | Median |
| Arresters connected to: | | | | | |
| 11-kv lines | 6 | 2 | 500 | 350 | 425 |
| 22-kv lines | 112 | 97 | 12,000 | 350 | 1,200 |
| 27-kv lines | 79 | 29 | 3,800 | Trace | 950 |
| 33-kv lines | 187 | 169 | 15,000 | Trace | 850 |
| 44-kv lines | 4 | 4 | 8,700 | 1,400 | 4,200 |
| 66-kv lines | 38 | 11 | 7,700 | 1,000 | 1,300 |
| 88-kv lines | 4 | 11 | 1,100 | Trace | 550 |
| 132-kv lines | 150 | 136 | 4,100 | Trace | 700 |
| Total | 580 | 459 | 15,000 | Trace | 950 |
| Arresters at stations with only one arrester and | | | | | |
| 1 line | 28 | 34 | 8,700 | Trace | 900 |
| 2 lines | 111 | 158 | 15,000 | Trace | 1,050 |
| 3 lines | 29 | 59 | 5,800 | Trace | 1,100 |
| 4 lines | 20 | 7 | 2,200 | 200 | 450 |
| 5 lines | 3 | 0 | | | |
| 6 lines | 4 | 2 | 800 | 600 | 700 |
| Arresters connected to: | | | | | |
| Wood-pole lines | | | | | |
| No ground wires | 107 | 166 | 12,000 | Trace | 1,100 |
| With ground wires | 187 | 72 | 5,200 | Trace | 900 |
| Steel-tower lines | | | | | |
| No ground wires | 32 | 26 | 1,800 | Trace | 850 |
| With ground wires | 192 | 151 | 11,000 | Trace | 650 |
| Mixed circuits | 62 | 144 | 15,000 | 250 | 1,000 |
| Total | 580 | 459 | 15,000 | Trace | 950 |

## Polarity of Currents

The polarity of 401 records, or 87.6 per cent of the total, was negative, and of 58, or 12.4 per cent, was positive. This proportion is intermediate between the previously reported values of 63 per cent negative for distribution arrester discharge currents,[1] and 95 per cent negative for lightning currents measured in steel tower legs of transmission lines.[5] In this investigation, the data do not show any recognizable effect of line construction, locality, or circuit voltage rating on the proportional numbers of negative and positive polarity records. Figure 5 shows that the distribution of the negative-polarity records with regard to current magnitude was substantially the same as for positive-polarity records.

## Variability Between Localities and Seasons

The data shown in figure 6 indicate that the number of arrester discharges varies considerably from season to season, and is consistently greater in some localities than in others. Seasons which are severe in some localities are comparatively mild in others. The greatest number of discharges per arrester per year was 3.84 for the Appalachian Electric Power Company in 1936, and the smallest number was 0.22 for the Indiana and Michigan Electric Company in 1938. The ratio between these two extremes is 17.5 to 1. During the entire period of the investigation, the average number for the former company was over 8 times that for the latter, although the average isoke-

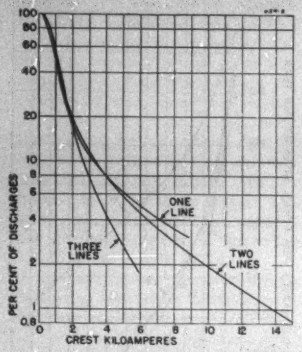


**Figure 8. Effect of number of connected lines on magnitude of currents discharged by arresters**

Curves show per cent of discharges with current magnitude at least as great as indicated, and include data only from stations with one arrester each

raunic level for the former location was less than twice that for the latter. Among the several factors which may have contributed to this difference are the flashover values of the lines involved, height of conductors above ground, presence of ground wires, and the frequency with which installations were inspected for magnetized links. However, when all known variables are taken into account, it is evident that the number and magnitude of discharge currents is strongly influenced by local conditions which can be evaluated only by experience over a period of several years. Therefore, it must be recognized that conditions may be encountered in service which are quite different from those reported here.

## Effect of Circuit Voltage

The data were examined to determine the effect of variation in the rated operating voltage on the severity of arrester discharge currents, but any consistent trend which may exist was obscured by other influences such as the effects of line construction and local conditions. It may be possible to evaluate this effect when more data are available.

## Effect of Line Construction

Figure 7 and table III show that arresters connected to wood-pole lines without ground wires are subjected to considerably more severe duty than are arresters on other types of circuits, particularly with regard to the number of high currents which they must discharge. They must pass currents of 5,000 amperes or more about ten times as often as other arresters. Less difference exists between the other types of construction included in figure 7.

**Table IV. Multiphase Arrester Operations**

| Type of Line Construction | Number of Cases Involving: One Phase Only | Two Phases | Three Phases |
|---|---|---|---|
| Steel towers, with ground wire | 55 | 21 | 18 |
| Steel towers, no ground wire | 13 | 2 | 3 |
| Wood poles, with ground wire | 38 | 11 | 4 |
| Wood poles, no ground wire | 30 | 26 | 28 |
| Mixed line construction | 11 | 6 | 7 |
| Total | 147 | 66 | 60 |
| | **Per Cent of Cases Involving:** | | |
| | **One Phase Only** | **Two Phases** | **Three Phases** |
| Wood poles, no ground wires | 35.7 | 31.0 | 33.3 |
| Other three types of construction | 64.2 | 20.6 | 15.2 |

## Effect of Multiple Circuits

In figure 8 are shown the results obtained at stations operating with only one lightning arrester each. The curves, shown for cases where one, two, or three transmission lines enter the station, indicate that there is some reduction in the magnitude of currents which the arrester must discharge, as the number of lines is increased. Five per cent of the recorded arrester currents exceeded 6,000 amperes where there was one line, 5,600 amperes where there were two lines, and 3,700 amperes where there were three lines.

It is significant that of the 85 three-pole arresters included in table II, including many at stations with several arresters, over 50 per cent were at stations with four or more incoming lines; yet all of the 11 arresters which produced ten or more records each were at stations with three lines or less.

## Multiphase Operations

Data from all arresters involved in the investigation are summarized in table IV to show how many times records of discharge current were found on only one phase of a three-pole arrester, on two phases simultaneously, and on all three phases simultaneously. This table indicates that for wood-pole lines without ground wires, more than one phase was involved in about two-thirds of the cases, and for other types of construction, more than one phase was involved in only about one-third of the cases. For each type of construction the number of two-phase operations was approximately equal to the number of three-phase operations.

## Discharge of Arresters Connected in Parallel

In some of the stations there was an arrester connected to each line where it entered the station, and additional arresters connected to the station bus or power transformers or both. The total number of three-pole arresters in any one station, so connected that they could operate directly in parallel, varied from one to ten. Data are presented in table V showing the number of times records of discharge currents were found simultaneously on several such arresters in one station, indicating that they probably discharged in parallel.

The maximum number of arresters apparently discharging in parallel, was five, in a case where there were but five arresters in the station. Three arresters

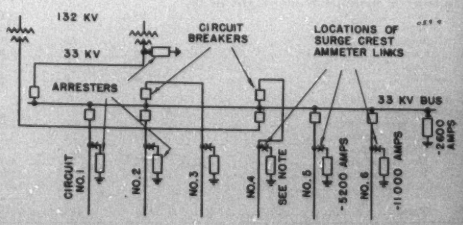


**Figure 9. One-line diagram of 33-kv connections at Newcomerstown substation, Ohio Power Company**

Current of −450 amperes recorded on phase 2 of this arrester. All other records on phase 1

discharged in parallel on three different occasions, with 4, 8, and 10 arresters respectively in the station, so connected that parallel operation was possible. Two arresters discharged in parallel on 24 different occasions, involving the same two arresters in 10 cases.

A case at a 33-kv substation is of particular interest. The circuit arrangement was as shown in figure 9. Circuits number 2 and number 5 in this sketch were on wood poles and the remaining circuits were on steel towers. All had overhead ground wires. A current of 11,000 amperes was discharged by one pole of the arrester on circuit number 6. Simultaneously a discharge of 5,200 amperes was recorded through the same phase of the arrester on circuit number 5, and one of 2,600 amperes was recorded through the same phase of the bus arrester. No discharges were recorded on the other phases of these arresters, and the only record obtained on the arresters on the other lines which were two, three, four, and five bays distant from the arrester which carried the heaviest current, was 450 amperes on another phase of the arrester connected to circuit number 4.

The curves of figure 10 show that the individual arrester currents discharged when two or more arresters discharge in parallel are in general higher than when only one of the parallel arresters discharges.

## Equipment Failures

The only failure of lightning arresters included in the four-year investigation, involved one old-type arrester operating under compromise conditions on a 132-kv circuit, with the possibility of voltage being applied in excess of the manufacturer's rating. This application was made in an attempt to protect power transformers which were of an old design, with an impulse strength considerably below present-day standards. It therefore appears that the arresters involved in the investigation have a discharge capacity adequate for discharges of the magnitude and duration which they experienced.

Five cases of bushing failure occurred. The bushings concerned were of an old type, some ten or more years old, and due to the fact that all cases were internal bushing failures, it is believed they are chargeable to deterioration rather than lack of adequate protection. In one case the current through the arrester was 12,000 amperes; in another case, 2,400 amperes; and in three cases, no currents were indicated. It is interesting to note that in all five cases, the bushings which failed were of the order of 30 to 70 circuit feet from the nearest lightning arrester. Four of the bushings were rated and operating at 33 kv and one at 22 kv.

One bus-support flashover occurred on a 33-kv bus. This was of an old design, the electrical characteristics of which are unknown.

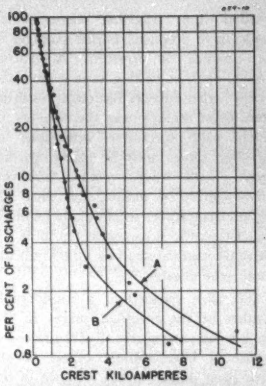


**Figure 10. Comparison of (A) discharge currents in cases where two or more arresters discharged in parallel, with (B) cases where only one of several parallel arresters discharged**

Curves show per cent of discharges with current magnitude at least as great as indicated

**Table V. Operation of Arresters Connected in Parallel**

| Number of Three-Pole Arresters in Station | Number of Three-Pole Arrester-Years | Number of Cases in Four Years When Records of Discharge Were Found Simultaneously on: One Arrester | Two Arresters | Three Arresters | Four Arresters | Five Arresters | Over Five Arresters |
|---|---|---|---|---|---|---|---|
| 1 | 195 | 142 | | | | | |
| 2 | 105 | 27 | 13 | | | | |
| 3 | 7 | 3 | 0 | 0 | | | |
| 4 | 67 | 7 | 5 | 1 | 0 | | |
| 5 | 62 | 11 | 2 | 0 | 0 | 1 | |
| 6 | 30* | 4 | 2 | 0 | 0 | 0 | 0 |
| 7 | 9 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 60 | 9 | 1 | 1 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 30 | 6 | 1 | 1 | 0 | 0 | 0 |
| Totals | 565* | 209 | 24 | 3 | 0 | 1 | 0 |

* Includes five two-pole arresters.

**Table VI. Protection Given by Arresters**

Assuming Two Circuits Connected to Bus, With Traveling Wave Entering on One

| Circuit Voltage Rating, Kv | Three-Pole Arrester-Years | Maximum Safe Impulse, Kv | Corresponding Discharge Current, Amperes | Number of Discharges Recorded: Total | Unsafe Without Arrester | Number of Single-Pole Discharges Per Three-Pole Arrester Per Year: Total | Unsafe Without Arrester |
|---|---|---|---|---|---|---|---|
| 11 | 6 | 104 | 296 | 2 | 2 | 0.33 | 0.33 |
| 22 | 112 | 144 | 340 | 97 | 97 | 0.87 | 0.87 |
| 27–33 | 266 | 180 | 368 | 198 | 176 | 0.74 | 0.66 |
| 44 | 4 | 232 | 460 | 4 | 4 | 1.00 | 1.00 |
| 66 | 38 | 324 | 596 | 11 | 11 | 0.29 | 0.29 |
| 88 | 4 | 412 | 720 | 11 | 4 | 2.75 | 1.00 |
| 132 | 150 | 600 | 1,000 | 136 | 47 | 0.91 | 0.31 |
| 11–33 | 384 | | | 297 | 275 | 0.77 | 0.72 |
| 44–88 | 46 | | | 26 | 19 | 0.57 | 0.41 |
| 132 | 150 | | | 136 | 47 | 0.91 | 0.31 |
| All | 580 | | | 459 | 341 | 0.79 | 0.59 |

## Protection Given by Arresters

The amount of benefit obtained from the arresters becomes apparent when calculations are made to show how many of the recorded disturbances would have resulted in voltages considered unsafe in the absence of arresters. In table VI, the values assumed for maximum safe impulse voltage are 80 per cent of the proposed AIEE and ASA standard chopped-wave impulse test voltages for new transformers. The corresponding arrester discharge current is calculated on a traveling wave basis, assuming one incoming and one outgoing transmission line, with an arrester at the station. All discharges recorded on lines of the rating in question, with currents above the calculated value, are then considered to have

resulted from traveling waves which would have produced unsafe voltages in the absence of arresters. A mathematical analysis on this basis is not valid for the higher-current discharges resulting from direct strokes near the stations, in which case successive reflections of traveling waves must be taken into account. Such waves would, however, almost surely be unsafe, and since the current magnitudes would likely be much higher than the values shown in table VI, the mathematical analysis would indicate them to be unsafe.

The table shows that a considerable number of the recorded surges in the 132-kv class, and nearly all of the recorded surges in lower-voltage classes would have been unsafe in the absence of arresters. The number of unsafe waves per three-pole arrester per year decreases progressively as system voltage is increased, ranging from 0.72 for 11–33 kv to 0.31 for 132 kv.

Note that the calculated values in table VI are based on the assumption that a traveling wave entered the station on one conductor only, and that there was a second three-phase line connected to the station bus to provide a path for an outgoing traveling wave. These assumptions were made to simplify the calculations, and appear to represent a fair approximation of the average conditions. For 7.4 per cent of the recorded discharges, dead-end circuits were involved, which would increase the severity as compared to that for the assumed conditions. For 75 per cent of the discharges, lightning currents entered the station over two or more conductors, which would also increase the severity. For 40 per cent of the discharges, there were more than two lines connected to the bus, which would reduce the severity.

## Conclusions

1. The data obtained indicate that the number and magnitude of discharge currents through arresters in stations is strongly influenced by local conditions and seasonal variations, and representative values can be determined only by experience over a period of several years. Therefore, conditions may be encountered in service which are quite different from those reported here.

2. A total of 459 single-pole arrester discharge currents were recorded in a four-year investigation, on an average number of 145 three-pole arresters located in stations. This is a rate of 0.79 single-pole discharges per three-pole arrester per year, which may be compared to the previously published rate of 0.51 discharges per single-pole arrester per year on rural distribution circuits, which have exposure somewhat comparable to transmission systems.

3. Additional discharges below the limit of current sensitivity of the recording apparatus probably occurred. Also in case of two or more discharges through any single-pole arrester between successive inspections, only one current record would be obtained; hence discharges undoubtedly occurred without being recorded for this reason.

4. One three-pole arrester yielded a total of 29 single-pole records during the four-year period, and three others yielded 24 each.

5. The highest discharge current recorded through one pole of an arrester was 15,000 amperes. There is no reason for believing that this is the highest discharge current that can occur, and it is expected that as more data are accumulated, substantially higher currents will be recorded.

6. Arresters at certain locations were subjected repeatedly to high discharge currents.

7. Approximately 3.5 per cent of the arrester discharge currents were of 5,000 amperes or more.

8. The polarity of 87.6 per cent of the records was negative, and of 12.4 per cent was positive. The proportion of positive currents was lower than previously obtained for distribution arrester discharge currents and higher than for lightning currents in steel tower legs of transmission lines.

9. The difference in number of records obtained in different localities during the four-year period was as great as eight to one. An attempt to evaluate the factors that might have contributed to this difference, such as the number of thunderstorm days per year, types of line construction, line operating voltage, and the interval between inspections to locate magnetized links, did not account for this great a difference in severities. It is evident that the severity is influenced by the severity of the storms, including seasonal variations, and other local factors that can be determined only by experience, and cannot be accurately predicted on the basis of data obtained in other localities.

10. Any consistent trend which may have existed in the severity of discharge currents, as influenced by the circuit voltage rating, was obscured by the effects of other variables. It may be possible to evaluate this effect when more data are available.

11. Arresters connected to wood-pole lines without ground wires were subjected to more high-current discharges than other arresters. Discharges of 5,000 amperes or more occurred about ten times as often as with other types of line construction.

12. For arresters connected to wood-pole lines without ground wires, more than one pole of the arrester was involved in about two-thirds of the cases when discharges were recorded. For arresters connected to other types of lines, more than one pole of the arrester was involved in only about one-third of the cases.

13. The data indicate that increasing the number of lines connected to a station bus decreases the magnitude of the current which any one lightning arrester in the station is required to discharge.

14. In stations where there were several arresters so connected that they could discharge directly in parallel, the records obtained indicate that five arresters discharged in parallel on one occasion, three arresters in parallel on three different occasions, and two arresters in parallel on 24 different occasions. The individual arrester discharge currents were in general higher when two or more arresters discharged in parallel, than when only one of two or more arresters in a station discharged.

15. The data indicate that when a lightning current enters a station on a line equipped with a lightning arrester at the station entrance, the lightning voltages reaching other parts of the station are not usually sufficient to cause the operation of other arresters.

16. Damage to equipment at stations during this four-year investigation was of minor importance. The only lightning arrester which failed was of an old type, applied under compromise conditions. The five cases of bushing failure involved 22- or 33-kv bushings of obsolete design, the insulation of which appeared to have been in doubtful condition.

17. Calculation of the traveling-wave voltages associated with the recorded arrester discharge currents shows that for 11- to 33-kv lines, about 0.72 records per three-pole arrester per year, or 93 per cent of those recorded, represented lightning voltages that would have been dangerous to station equipment in the absence of arresters. Corresponding values for 44- to 88-kv lines are that 0.41 records per three-pole arrester per year, or 73 per cent of those recorded; and for 132-kv lines that 0.31 records per three-pole arrester per year, or 35 per cent of those recorded, would have been dangerous to station equipment in the absence of arresters. This clearly illustrates the relative number of lightning surges of dangerous magnitude which reach a station not supplied with lightning-arrester protection.

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## Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

# Electric Couplings

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**Synopsis:** Electric couplings have recently been applied on a large scale in geared Diesel ship drives to couple the engines to the gear. They serve a threefold purpose by acting as a flexible coupling to keep the torsional vibration of the engine out of the gears, as a disconnecting clutch to enable any engine to be cut out of service, and as an aid in maneuvering.

A typical large coupling built for marine service is described, and the general principles and characteristics of this type of device are given. Results of tests taken to confirm the calculated characteristics are included. The operation of the coupling as an aid in maneuvering is described. A summary of applications to date is given with a discussion of possible applications other than ship drive.

ELECTRIC COUPLINGS are devices for transmitting torque by means of electromagnetic forces in which there is no mechanical contact between the driving and driven members. Thus, they differ from electromagnetic clutches which are only friction clutches in which an electromagnet is used to apply the pressure between the friction surfaces. Electric couplings are not new in principle, but their application on a large scale has come only in the last few years. It is the purpose of this paper to review the principles of operation of electric couplings, describe their major application to geared Diesel-engine ship propulsion, and discuss the engineering problems associated with this application.

Probably the idea of an electric coupling is nearly as old as the idea of an a-c generator. There are a number of early United States patents from 1891 to 1906 describing at least the elements of the various types of electric couplings. In 1934 and 1935, the authors made a study of the various types of couplings with the hope of applying them to marine drives. Since 1935, A.S.E.A. in Sweden have equipped a number of ships with electric couplings.[1,2] A 3,000-horsepower coupling was supplied by the Westinghouse Electric and Manufacturing Company to the United States Navy and was quite thoroughly tested. At about the same time, two tankers were equipped with 750-horsepower couplings made by the Elliott Company. Within the past year, the United States Maritime Commission has purchased 116,000 shaft horsepower in electric couplings in 48 units to equip 20 vessels. The extent of electric coupling applications for marine service in this country is given by table I.

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1. For all numbered references, see list at end of paper.

## Principles of Operation

The electric slip coupling is the type used on all of the large marine applications, and the discussion of the numerous other types will be reserved till the end of the paper. The slip type has poles excited by direct current on one rotating member, and an armature winding, usually of the squirrel-cage type, on the other rotating member. If it is necessary to vary the speed, the winding can be insulated and brought out to slip rings, so that an external resistance can be connected in the circuit to vary the slip.[3] Any relative motion or slip between the two members will induce currents in the armature winding which react with the flux to produce a torque tending to hold the two members close together in speed. This is similar in action to the usual induction motor, except that the rotating field is produced by a direct current in a rotating member instead of by polyphase currents in a stator.

## Application to Marine Drives

The principal application of the electric coupling is in geared Diesel-engine ship-propulsion drives as listed in table I. Other applications are described at the end of the paper. The arrangement of a typical marine application is shown in the sketch in figure 1. This is the arrangement being used on the four Maritime Commission *C*-3 cargo vessels listed as number 3 in table I. The four engines drive the single screw through four electric couplings and a two-pinion gear. The manner of mounting the couplings on the engine can be seen in figure 2, and the two members of the coupling are shown in figures 3 and 4.

The coupling performs four functions in the drive, as follows:

1. It acts as a torsionally flexible member between the engine and the gear, eliminating all shocks and limiting the transmission of torsional vibrations produced by the engine to a negligible amount.

2. Since there is no mechanical connection between the two members, the coupling permits a small amount of misalignment. This facilitates the erection of the propulsion plant and increases the reliability in service.

3. It acts as a quick-disconnecting clutch which is not subject to wear, and the torque of which is independent of speed. Any engine can be disconnected in less than a second by interrupting the field current of its coupling. This permits repairs to be made without stopping the ship, and some of the engines can be shut down at low speeds to give greater economy. The greater reliability of multiple-engine drives can be realized only if a disconnecting clutch is available to cut out a faulty engine, enabling the ship to proceed on the good engines. The use of the coupling as a clutch aids in maneuvering as described below.

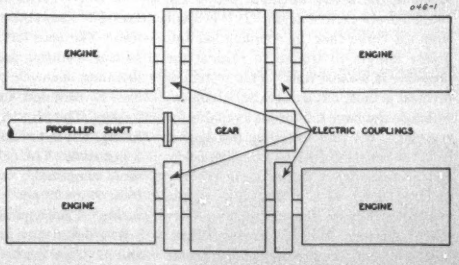


**Figure 1. Arrangement of four-engine geared ship-propulsion drive for United States Maritime Commission C-3 cargo vessels, rated 8,500 shaft horsepower**

4. The coupling limits the maximum torque to a safe value. The steady-state pull-out torque is usually about 150 per cent and the transient maximum torque on suddenly applied loads is about 200 per cent. If trouble develops on one engine, such as a seized piston, the electric coupling will limit the torque transmitted to this engine to twice the normal value, and will permit it to stop without injuring the gear and with minimum damage to the engine.

The ease with which electric couplings can be connected and disconnected en-

ables them to be used in maneuvering the ship in a manner which is impossible with other forms of couplings. When a large amount of maneuvering is to be done at low speed, as in going through a close channel or approaching or leaving the dock, the ship can be maneuvered entirely by the use of the couplings. This is done by running half of the engines ahead and the other half astern. The propeller can be connected to either group of engines by energizing the corresponding couplings, and the ship closely controlled by one coupling control lever. This system saves on starting air for the engines, and approaches the Diesel-electric drive in convenience.

The couplings can also be used to reverse the propeller in reversals from full ahead to full astern, as in a "crash stop". In such a reversal, the coupling excitation is removed and the engines reversed. After they are running on fuel at reduced speed in the astern direction, the coupling fields are energized, and the coupling torque reverses the propeller. Figure 5 shows a test slip torque curve on a coupling and a typical propeller torque curve during reversal,[3] assuming that the engines have been brought to 60 per cent speed in the astern direction before the couplings are excited again. It is evident from the curve that the coupling has sufficient margin in torque to reverse the propeller in a short time. This system of reversal is most advantageous on engines which do not have full torque available for reversal. By disconnecting the engine from the inertia of the gear, coupling fields, and propeller, they can be reversed very quickly, even with rather low torque available, because the inertia to be accelerated is low. With the engine on fuel, full torque becomes available to reverse the heavy inertias of the system and overcome the propeller torque. If the engine has sufficient reversing torque, the maneuvering can be done entirely with the engine, with the coupling acting like a solid coupling.

## Characteristics

*Losses.* There are only three losses in electric couplings—windage, slip or armature $I^2R$ loss, and excitation or field $I^2R$ loss. The core loss is usually negligible, as the operating frequency is ordinarily less than one cycle per second. The core loss is included in the measured slip losses. The slip varies with speed and rating, but is ordinarily between one and 2 per cent. The field loss has about the same magnitude, so the efficiency varies from 95 to 98 per cent depending on the rating. The coupling illustrated in figures 1 to 4 tested just under 1.1 per cent slip and 97.75 per cent efficiency.

**Figure 2. Electric coupling mounted on 2,225-horsepower, 240-rpm Diesel engine on shop tests**

This is the engine and coupling for the drive in figure 1

*Torques.* The torques required are determined by the operating conditions for the particular drive. The Maritime Commission engineers realized the full possibilities of using the electric coupling for maneuvering. They specified a minimum torque of 75 per cent for any slip up to 140 per cent to give the coupling some margin in torque over that required by the propeller during reversal. They also specified 150 per cent pull-out, or maximum torque as being sufficiently high to cover all conditions of operation. To obtain high torques at high slips, and at the same time maintain low slip at normal load and minimum weight and space, is a real design problem. Earlier couplings employed single-deck squirrel cages, although some of them used deep bars. The torques of these couplings at high slips were far below the values necessary to reverse the propeller at full ship speed. All couplings being built to the Maritime Commission specifications employ some

**Table I. List of Marine-Type Electric Couplings**

Completed or Under Construction in United States of America, as of November 15, 1939

| Number | Type of Vessel | Number of Ships | Ship Builder | Engines Per Ship | Engine Manufacturer | Engine Horsepower | Rating, RPM | Coupling Manufacturer | Gear Manufacturer |
|---|---|---|---|---|---|---|---|---|---|
| 1** | | | | 1 | | 3,000 | 400 | W | |
| 2 | Tanker | 2 | C, M | 2 | F-M | 750 | 400 | E | F-B |
| 3 | † | 1 | | 1 | Atlas | 600 | 300 | D | Falk |
| 4* | C-3 cargo | 4 | Sun | 4 | Busch | 2,225 | 240 | W | Falk |
| 5* | C-3 cargo and passenger | 4 | Sun | 2 | Sun | 4,375 | 180 | W | W |
| 6* | C-1 cargo | 5 | ST | 2 | HOR | 2,140 | 240 | W | W |
| 7* | C-1 cargo | 5 | W.P.&S. | 2 | Busch | 2,085 | 233 | E | F-B |
| 8* | C-1 cargo | 2 | Penna | 2 | Nord | 2,105 | 220 | W | W |

* United States Maritime Commission vessels.
** Experimental unit for United States Navy. Not installed in a ship.
† The "Bear", Antarctic exploration ship, recently repowered for Byrd expedition.

Key to abbreviations:

C—Collingwood Ship Yards, Ltd.
M—Marine Industries, Ltd.
Sun—Sun Shipbuilding and Dry Dock Company
ST—Seattle Tacoma Shipbuilding Company
W.P.&S.—Western Pipe and Steel Company
Penna.—Pennsylvania Ship Yards
Atlas—Atlas Imperial Diesel Engine Company
Busch—Busch-Sulzer Bros. Diesel Engine Company
HOR—Hoover-Owens-Rentschler Division of General Machinery Corporation
Nord.—Nordberg Manufacturing Company
F-M—Fairbanks-Morse Company
W—Westinghouse Electric and Manufacturing Company
E—The Elliott Company
D—Dynamatic Corporation
F-B—Farrell-Birmingham Company
Falk—The Falk Corporation

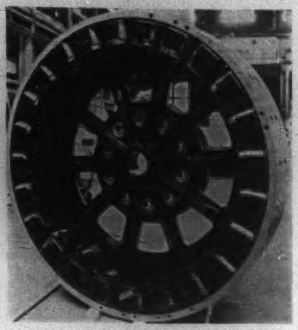

Figure 3. Field member of coupling shown in figure 2

form of double-deck squirrel-cage armature winding to increase the resistance at high slips.

*Temperatures.* All recent couplings have had guaranteed temperature rises of 70 degrees centigrade by resistance, above an ambient of 50 degrees centigrade. These are standard for class *B* insulation on electrical installations in ship engine rooms. This rise applies only to the field, as in the squirrel-cage type of armature there is no insulation, and the temperature is limited solely by mechanical considerations. It is customary to require that the coupling meet the guaranteed temperature rise when transmitting full torque down to 70 per cent of normal speed. This speed was chosen as it is the speed obtained with full torque on half of the engines, and was considered the most severe operating condition likely to be encountered. Theoretically, it would be possible to operate with full torque at half speed when running on one engine of a four-engine drive, but it was not considered that this would be an operating condition. With class *B* asbestos and mica insulation, the machine is practically incombustible and offers much less fire hazard than any device using oil.

*Torsional Characteristics.* In the cases studied so far by the authors, the electrical coupling has effectively limited the transmission of torsional vibration from the engine to the gears to negligible values. It has also had negligible effect on the critical speeds of the engine. In information previously published about electric slip couplings,[3] it has been said that the coupling does not transmit the torque pulsations originating in the engine. Strictly speaking, this statement is not exactly true, because as shown in appendix *A*, the electric coupling under the influence of pulsating torques acts as a weak elastic member, or a torsional spring of low spring constant. In appendix *B*, there is a further discussion of the effects of this spring constant, giving the reasons why it has negligible effect on the natural frequencies of the engine and at the same time effectively limits the vibrations transmitted from the engine.

## Structural Features

The coupling illustrated in figures 2, 3, and 4 is typical of large marine couplings made in this country, especially those for Maritime Commission vessels. The two members are overhung on the gear and engine shafts. Most of the couplings have the inner member mounted on the engine shaft, but the coupling will transmit torque in either direction and the field can be put on the engine. The arrangement to be used depends largely on the amount of inertia desired by the engine manufacturer for satisfactory operation of the engine and the most advantageous placing of the critical speeds.

The field has the poles bolted to the inside of the rim of a fabricated-steel spider. The spider has a flange for bolting to the pinion shaft. The field is put on the outer member because such an arrangement gives more room for the winding, better ventilation, and more accessibility for replacing coils. The coils are made of edgewound copper strap with class *B* insulation of the same type almost universally used in large a-c motors and generators, representing the most rugged construction available. Repairs can be made quite easily by unbolting the pole, sliding it out axially, and installing a spare field coil. The collector rings are bronze and the collector assembly is split for ease of removal. The field is ventilated by air which is taken in through holes in the spider plate, passes axially along the windings, and is discharged at the open end.

The inner member consists of a fabricated spider which has a flange for bolting to the engine crankshaft flange. The core is made of one piece circular punchings shrunk on the rim of the spider. The winding is a double-deck squirrel cage with separate short-circuiting end rings for each layer. The outer layer of high-resistance bars is generously proportioned to absorb the heat produced during reversal of the propeller, since at high slips most of the loss is in the outer layer.

The coupling can be removed or assembled without disturbing the crankshaft or pinion shaft. Provision has been made to move the two members together axially a sufficient amount so that they will clear the spigot fits. In this position, they are centered together by a centering fit and can be bolted together. The entire unit can then be lifted out between the two shafts.

A screen guard is usually placed around the coupling for the protection of the engine room personnel. The brush holder parts are mounted on the gear case. The couplings take their excitation from the ship auxiliary power supply. The control consists of a selector switch operated by the coupling control lever at the engine control station, ammeters to indicate the field current, circuit breakers in each coupling circuit for short-circuit protection, and suitable magnetically operated contactors. Discharge resistors are provided and also a resistor to reduce the coupling field for long operating periods at low speed and low torque. The necessary interlocks are provided to prevent energizing a coupling when the corresponding engine is shut down.

The size and weight of a coupling of given rating increase quite rapidly with the air gap. The minimum gap which can be used is determined by the possible maximum unbalanced magnetic pull. The unbalanced magnetic pull acts in a radial direction and is proportional to the displacement for magnitudes of displacement encountered in normal operation. It acts to increase the displacement, so is equivalent to a negative restoring force.

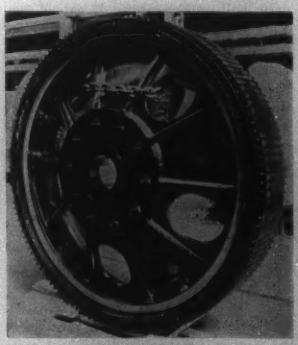

Figure 4. Armature or squirrel-cage member of coupling shown in figure 2

The magnitude of the force depends on the initial displacement which is a function of the bearing clearance, the accuracy of the original alignment, and the possible distortion or misalignment of the ship structure. With conventional

ship structure, the misalignment due to the distortion of the ship is very small, as a large deflection of the center of the ship with respect to the ends is produced by a small shear deformation. The air gap used represents a compromise between

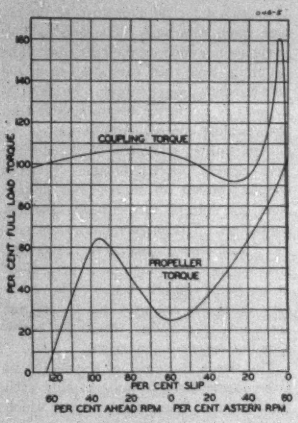


**Figure 5. Test slip-torque curve of coupling shown in figures 1 to 4**

A typical propeller-torque curve during reversal from full speed is shown assuming that the engine has been brought to 60 per cent speed astern before the couplings are excited

size and weight on the one hand and magnetic pull on the other. A gap of one-fourth inch appears to be a good compromise for large couplings. Since the magnetic pull may be increased by large bearing clearances, it is desirable to keep these clearances to a minimum consistent with good practice. It should be noted that the magnetic pull in an axial direction is very small.

## Tests

Since the coupling described above was the first coupling to be delivered to the Maritime Commission, it was given rather extensive tests. The slip-torque curve was measured by locking one member of the coupling through a beam and scale and driving the other member at various speeds with a large d-c motor. The torque measured on the scale was checked by readings of the input to the driving motor. The results are shown in figure 5. The windage was measured by driving the coupling at various speeds and measuring the input. From the curve of friction and windage against speed, the windage could be separated out by the assumption that the friction loss varied directly with the speed while the windage varied as the cube of the speed. The ability of the squirrel cage to undergo a large number of maneuvering operations at reduced speed was demonstrated by locking the inner member, bringing the field member to 70 per cent speed with the excitation off, and then stopping it by applying the excitation. This was repeated 22 times in 9 minutes and 12 seconds with no injurious heating of the bars. Of course, there was no propeller torque to overcome, but the addition of the driving motor gave an inertia comparable to the final installation, and it was felt that the test demonstrated that the coupling had considerable margin above the requirements of actual service.

Further tests were taken on the coupling at the engine-builder's plant. The coupling was mounted on the engine as shown in figure 2, coupling it to a water brake. All of the regular tests on the engine were taken by loading it on the brake through the coupling. This also provided an opportunity for a full-load temperature test on the coupling, demonstrating that it met its guarantees with a good margin. The test setup included a flywheel on the brake side which was roughly equivalent to the mass of the gears and propeller in the final installation. The maneuvering of the ship was simulated, although it was not possible to include propeller torque, and the coupling was able to reverse the mass of its outer member and the flywheel from full speed ahead to full speed astern in from six to eight seconds. The tests indicated that some time in reversal of the propeller would be saved by reversing the engine independently with the coupling disengaged and then using the coupling to stop and reverse the propeller. Several torsiograph records were made to determine the amount of vibration transmitted through the coupling. Typical examples are shown in figure 6. The record marked *A* was taken on the engine crankshaft flange. The vibrations present are the seventh order, or the main firing frequency. They are speed variations rather than shaft vibrations. The record marked *B* was taken on the brake side of the electric coupling. None of the seventh order impulses can be seen on this record. The long swings are due to the natural period of the torsiograph. The high-frequency variations seem to have a frequency of 12 per revolution, and are probably excited by the brake. The amplification on the two records is about the same, record *B* being slightly higher than *A* as shown by the calibration for one degree indicated on the record. The revolution marked off in each record is the same revolution of the engine.

## Other Types of Electric Couplings

There are as many possible types of electric couplings as there are types of motors and generators. The more practical types will be discussed briefly.

The slip coupling with squirrel-cage winding has been described in detail. For the purpose of obtaining variable speed, it is possible to insulate the armature winding and bring the leads out through slip rings exactly as in a wound-rotor induction motor. This type will be referred to as a wound-rotor coupling. The problem of controlling the speed through the external resistance is exactly the same as for the wound-rotor motor, except that it is possible to get fine speed adjustments

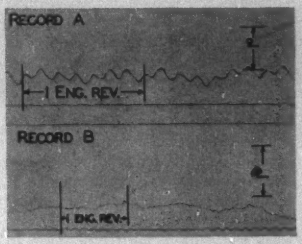


**Figure 6. Typical torsiograph records, taken on shop test with engine driving water brake through electric coupling**

Record *A* taken on engine crankshaft flange
Record *B* taken on output side of electric coupling

between resistance points by controlling the field current. The efficiency comes down nearly proportional to the slip. This type may find application to Diesel-engine drives where it is desired to run below the lowest operating speed of the engine.

A variable-speed coupling for certain types of load may also be obtained by designing a squirrel-cage slip coupling for high slip and controlling the torque by control of the excitation. This is analogous to controlling the voltage on a squirrel-cage motor. There are two difficulties in this: The high slip necessary for any appreciable range of slip by field control results in lower efficiency at full speed as well as at reduced speed. The other difficulty is the dissipation of the heat from the armature member, since all the slip losses go into this member.

Instead of a conventional squirrel-cage winding, it is obviously possible to use only a solid steel rotor on the armature, making use of the eddy currents induced in its surface. This type gives less pull-out torque and higher slip for the same air gap surface and weight. However, for variable speed by field control, it has the advantage that it can be arranged more readily to dissipate the high slip losses, especially in smaller sizes.

The inductor-alternator principle may be used to make an inductor-type electric coupling. The field is wound peripherally on one member, dividing the air gap into two sections. The flux is unidirectional in each section and is caused to alternate in the armature winding by the relative motion of inductor teeth on the other member. For a given air gap and pull-out torque, more air-gap surface is required in the inductor-type machine since the useful alternating-flux density is limited by saturation to about half of the value in a salient-pole type, due to the superposition of d-c and a-c components of flux. However, where the air gap can be kept very small, this type may result in somewhat cheaper construction for small couplings.

A synchronous coupling can be built by using salient poles and d-c excitation on both members. For most applications this type is less desirable than the slip coupling for several reasons. The increased excitation requirements partially offset the elimination of slip losses, and slip rings are required on both members. The synchronous "spring" torque tends to be higher than in the slip coupling, and if this type of coupling should pull out of step with fields excited, high values of slip-frequency alternating torque would be developed which might excite the torsional natural frequency of the connected mechanical system. Also the presence of field windings on both members makes it difficult to obtain high average torques at high slip.

## Other Applications

The application of the slip type of coupling to geared Diesel ship-propulsion drives has been discussed in considerable detail, because that is the largest application of couplings made so far. However, it is interesting to note some of the other possible uses for couplings. This same type of coupling can be applied to any Diesel or gas engine where it is desired to limit the engine torque impulses transmitted to the load. It may also be used for the purpose of limiting the maximum torque and avoiding stalling of the engine. In such applications, the pull-out torque of the coupling must be made less than the stalling torque of the engine. It can be used as a disconnecting clutch to shift gears on an engine which is too large for a friction clutch.

The variable-speed coupling of either the wound-rotor or high-slip squirrel-cage type may be used with a synchronous motor or a constant-speed induction motor to obtain smooth speed or torque control. By use of field control, the speed can be controlled in finer steps than is practicable with a resistance in the secondary of a wound-rotor induction motor. As previously stated, the reduced speed is always accompanied by a reduction in efficiency, but this may not be too serious a handicap for a limited range in speed, for short-time operation at low speed, or for fan or pump drives where the power varies as the cube of the speed.

For a limited range of speed, or for a fan type of load, it is possible in the smaller ratings to obtain speed control entirely with field control of the coupling, using a slip type of coupling with high-resistance squirrel cage, or a solid steel armature.

## Conclusions

The electric coupling has filled a definite need in the application of higher-speed Diesel engines to geared ship propulsion. The engineering problems encountered in this application have been satisfactorily solved, as proved by the installations which are now in successful service. As time goes on, a larger proportion of Diesel ship drives are being geared, and the percentage of these geared drives on which electric couplings are applied is increasing rapidly.

Now that the electric coupling has been developed and applied on a commercial scale, it is quite sure to find other applications where its characteristics can be used to advantage.

# Appendix A

## Electrical Torques Produced by Pulsating Motion in the Electric Slip Coupling

The analogy to the induction motor makes it apparent that the effect of the average torque is to produce a slip between the two members. The effect of any superimposed alternating motion between the two members is to produce both in-phase and quadrature components of alternating torque.

The component of torque in phase with the alternating component of the relative velocity is a damping torque, since it represents energy supplied by the alternating motion. The component of the alternating torque in phase with the angular motion (but opposite in direction) is a transient synchronizing torque, and is equivalent to a weak mechanical spring as far as alternating components of torque are concerned.

The mathematical analysis is based on the following assumptions:

1. That the field resistance is negligible in comparison with the field reactance at the frequencies to be considered.

2. That the squirrel-cage winding can be replaced by an equivalent two-phase winding. This has been proved by applications to induction motors to be quite accurate.

3. That the inductance ($L$) of these equivalent armature circuits is independent of the relative position with respect to the field. This, in general, is only approximately true, but the effects of variation in inductance will be analyzed further from a physical point of view.

4. The analysis will be carried through for a relative angular motion represented by $\theta = (\omega_s t + \theta_\Delta \sin \omega_\Delta t)$, where $\theta$ is the relative angular position of phase $a$ with respect to the field, $\omega_s$ is the average angular velocity, $\theta_\Delta$ is the amplitude of the alternating angular motion, and $\omega_\Delta$ is $2\pi$ times the forced frequency of oscillation. All angles are measured in electrical radians. The actual alternating motion may not be sinusoidal, but it can be resolved into a series of sinusoidal components which can be treated in the same manner.

5. That the amplitude of the angular oscillation $\theta_\Delta$, is small, so that $\cos(\theta_\Delta \sin \omega_\Delta t)$ can be taken as unity and $\sin(\theta_\Delta \sin \omega_\Delta t)$ can be taken as $\theta_\Delta \sin \omega_\Delta t$. This is a good approximation up to about 15 electrical degrees. This maximum angle corresponds to about 50 per cent torque transmitted, which is higher than is likely to be encountered. On this basis:

$$\cos\theta = \cos\omega_s t + \frac{\theta_\Delta}{2}\cos(\omega_\Delta+\omega_s)t - \frac{\theta_\Delta}{2}\cos(\omega_\Delta-\omega_s)t$$

$$\sin\theta = \sin\omega_s t + \frac{\theta_\Delta}{2}\sin(\omega_\Delta+\omega_s)t + \frac{\theta_\Delta}{2}\sin(\omega_\Delta-\omega_s)t$$

The equation for voltage and current will be expressed first in volts, amperes, and ohms, and then the torque equation will be expressed in per unit notation in order to give both forms.

$$e_a = -p\left(\frac{M}{L_f}\psi_f\right)\cos\theta = \left(\frac{M}{L_f}\psi_f\right)\Big[\omega_s \sin\omega_s t + \frac{\theta_\Delta}{2}(\omega_\Delta+\omega_s)\sin(\omega_\Delta+\omega_s)t - \frac{\theta_\Delta}{2}(\omega_\Delta-\omega_s)\times \sin(\omega_\Delta-\omega_s)t\Big]$$

$$e_b = -p\left(\frac{M}{L_f}\psi_f\right)\sin\theta = -\left(\frac{M}{L_f}\psi_f\right)\times \Big[\omega_s\cos\omega_s t + \frac{\theta_\Delta}{2}(\omega_\Delta+\omega_s)\cos(\omega_\Delta+\omega_s)t + \frac{\theta_\Delta}{2}(\omega_\Delta-\omega_s)\cos(\omega_\Delta-\omega_s)t\Big]$$

The currents can be calculated by using the proper impedance for each frequency. The subscripts $s$, $\Delta+$, and $\Delta-$ will be used to indicate the impedances determined at frequencies $\frac{\omega_s}{2\pi}$, $\frac{\omega_\Delta+\omega_s}{2\pi}$, and $\frac{\omega_\Delta-\omega_s}{2\pi}$ respectively.

$$i_a = \left(\frac{M}{L_f}\psi_f\right)\Big[\frac{\omega_s}{(Z_s)^2}(\gamma_s\sin\omega_s t - X_s\cos\omega_s t) + \frac{\theta_\Delta}{2}\frac{(\omega_\Delta+\omega_s)}{(Z_{\Delta+})^2}\{(\gamma_{\Delta+})\sin(\omega_\Delta+\omega_s)t - (X_{\Delta+})\cos(\omega_\Delta+\omega_s)t\} - \frac{\theta_\Delta}{2}\frac{(\omega_\Delta-\omega_s)}{(Z_{\Delta-})^2}\times \{(\gamma_{\Delta-})\sin(\omega_\Delta-\omega_s)t - (X_{\Delta-})\cos(\omega_\Delta-\omega_s)t\}\Big]$$

$$i_b = -\left(\frac{M}{L_f}\psi_f\right)\left[\frac{\omega_s}{(Z_s)^2}(\gamma_s \cos \omega_s t + X_s \sin \omega_s t) + \frac{\theta_\Delta}{2}\frac{(\omega_\Delta+\omega_s)}{(Z_{\Delta+})^2}\{(\gamma_{\Delta+}) \cos (\omega_\Delta+\omega_s)t + (X_{\Delta+}) \sin (\omega_\Delta+\omega_s)t\} + \frac{\theta_\Delta}{2}\frac{(\omega_\Delta-\omega_s)}{(Z_{\Delta-})^2} \times \{(\gamma_{\Delta-}) \cos(\omega_\Delta-\omega_s)t + (X_{\Delta-}) \sin (\omega_\Delta-\omega_s)t\}\right]$$

In per-unit notation, the torque can be determined by the equation developed by R. H. Park[4] and others.

$$T = (i_a\psi_b - i_b\psi_a) \qquad (1)$$

The per-unit currents can be obtained by dividing the actual amperes by rated amperes ($I_0$). The per-unit flux linkage, $\psi_a$ and $\psi_b$ can be obtained by dividing actual interlinkage by $\psi_0$ which is the flux linkage corresponding to the resistance drop at full load.

The net flux linkage of each armature circuit can be written:

$$\psi_a = \frac{1}{\psi_0}\left(\frac{M}{L_f}\psi_f \cos\theta + i_a L\right)$$

$$\psi_b = \frac{1}{\psi_0}\left(\frac{M}{L_f}\psi_f \sin\theta + i_b L\right)$$

Then

$$T = \left(\frac{M\psi_f}{L_f\psi_0}\right)(i_a \cos\theta - i_b \sin\theta) \qquad (2)$$

Expanding this equation and neglecting all $\theta_\Delta^2$ terms because they are small for $\theta_\Delta$ less than 15 degrees as assumed, and keeping impedances in ohms:

$$T = \left(\frac{M\psi_f}{L_f\psi_0}\right)^2\frac{\psi_0}{I_0}\left[\left\{\frac{\omega_s\gamma_s}{Z_s^2}\right\} + \left\{\frac{(\omega_\Delta+\omega_s)\gamma_{\Delta+}}{(Z_{\Delta+})^2} + \frac{(\omega_\Delta-\omega_s)\gamma_{\Delta-}}{(Z_{\Delta-})^2}\right\}\frac{\theta_\Delta}{2}\cos\omega_\Delta t + \left\{\frac{(\omega_\Delta+\omega_s)X_{\Delta+}}{(Z_{\Delta+})^2} + \frac{(\omega_\Delta-\omega_s)X_{\Delta-}}{(Z_{\Delta-})^2} - \frac{2\omega_s X_s}{(Z_s)^2}\right\}\frac{\theta_\Delta}{2}\sin\omega_\Delta t\right] \qquad (3)$$

Using per-unit impedances, and using the symbols $s$ and $\Delta$ to represent the per-unit slip frequency and forced frequency respectively, the torque may be written in per-unit notation:

$$T = (E_d')^2\left[\frac{\frac{\gamma_s}{s}}{\left(\frac{\gamma_s}{s}\right)^2+(X_s)^2}\right] + (E_d')^2 \times \left[\frac{\frac{\gamma_{\Delta+}}{\Delta+s}}{\left(\frac{\gamma_{\Delta+}}{\Delta+s}\right)^2+(X_{\Delta+})^2} + \frac{\frac{\gamma_{\Delta-}}{\Delta-s}}{\left(\frac{\gamma_{\Delta-}}{\Delta-s}\right)^2+(X_{\Delta-})^2}\right] \times \frac{\theta_\Delta}{2}\cos\omega_\Delta t + (E_d')^2\left[\frac{X_{\Delta+}}{\left(\frac{\gamma_{\Delta+}}{\Delta+s}\right)^2+(X_{\Delta+})^2} + \frac{X_{\Delta-}}{\left(\frac{\gamma_{\Delta-}}{\Delta-s}\right)^2+(X_{\Delta-})^2} - \frac{2X_s}{\left(\frac{\gamma_s}{s}\right)^2+(X_s)^2}\right]\frac{\theta_\Delta}{2}\sin\omega_\Delta t \qquad (4)$$

In this equation, $E_d'$ is the per-unit voltage proportional to $\frac{M\psi_f}{L_f}$, the flux which would link the armature if the circuit were opened and constant field flux, $\psi_f$ maintained. In dealing with transient phenomena, this voltage would be called the voltage back of transient reactance.

From these torque equations, it is apparent that there is a steady torque dependent only on the average slip, $s$, and two alternating components, the $\sin \omega_\Delta t$ and $\cos \omega_\Delta t$ terms. The amplitudes of these alternating components are a function of the two frequencies $\Delta+s$ and $\Delta-s$. The sine term is in phase with, but opposed to the displacement and is, therefore, analogous to a weak mechanical spring connecting the two members. The magnitude of this spring constant is simply:

$$\frac{P(E_{oc}')^2}{4}\left[\frac{X_{\Delta+}}{\left(\frac{\gamma_{\Delta+}}{\Delta+s}\right)^2+(X_{\Delta+})^2} + \frac{X_{\Delta-}}{\left(\frac{\gamma_{\Delta-}}{\Delta-s}\right)^2+(X_{\Delta-})^2} - \frac{2X_s}{\left(\frac{\gamma_s}{s}\right)^2+X_s^2}\right]T_0$$

Where $P$ is the number of poles in the coupling and $T_0$ is rated torque. If $T_0$ is in pound-feet, the constant is in pound-feet per radian.

The cosine term is a torque in phase with the alternating component of the velocity, and is analogous to mechanical velocity damping. The damping coefficient is:

$$\frac{P(E_{oc}')^2}{4\omega_\Delta}\left[\frac{\left(\frac{\gamma_{\Delta+}}{\Delta+s}\right)}{\left(\frac{\gamma_{\Delta+}}{\Delta+s}\right)^2+(X_{\Delta+})^2} + \frac{\left(\frac{\gamma_{\Delta-}}{\Delta-s}\right)}{\left(\frac{\gamma_{\Delta-}}{\Delta-s}\right)^2+(X_{\Delta-})^2}\right]T_0$$

If $T_0$ is in pound-feet, the coefficient is in pound-feet per radian per second.

From the torque equation (2), it is seen that the pulsating components result from the action of the quadrature axis components of current ($i_a \sin\theta - i_b \cos\theta$). In order to simplify the derivation, the direct and quadrature axis reactances were assumed equal, but if they differ appreciably, the quadrature axis value should be used. If there are damping circuits on the field poles other than the field winding, they must be considered as affecting the reactance at the high frequencies.

## Appendix B

### Influence of the Electric Coupling on the Torsional Vibrations of the Propelling Drive

An important function of the electric coupling is to limit the transmission of torsional vibration from the engine to the gear. In the information published about electric couplings, it has often been stated that the electric coupling transmits only torques proportional to the slip, and therefore from the standpoint of torsional vibration separates the two systems on each side of it completely. As demonstrated in appendix *A*, this is not strictly true as the coupling acts as an elastic member having a spring constant which is a function of the frequency of the applied torque. It is zero at zero frequency and approaches a maximum value as the frequency increases. When a pulsating torque is applied to the coupling, a certain amount of energy is dissipated in the coupling. This energy acts as damping. For low frequencies up to one cycle per second, it is constant and equal to the torque normally produced in the coupling at normal slip, and then decreases rapidly as the frequency increases, being approximately inversely proportional to the frequency.

The electric coupling being located near the node of the vibration in the crankshaft, the damping in the coupling has very little influence on the amplitude of vibration in the engine. The damping in the coupling will be very effective in limiting the amplitude of low-frequency vibrations originating in the propeller if the nodes are such that large relative motions are produced in the coupling.

On high-speed Diesel engines, the low spring constant of the electric coupling has practically no influence on the natural period of torsional vibrations of the engine proper. Due to the small mass of the inner part of the electric coupling mounted on a very rigid crankshaft, this natural period is very high and only the critical speeds of high orders are in the operating range of the engine. Only an inappreciable part of these torque harmonics is transmitted through the coupling to the gears.

The effect of the spring constant of the electric coupling on the complete propelling drive is to produce a natural period of vibration of low frequency which might be in the range of the frequency of the torque impulses produced by the propeller blades cutting the wake of the ship. Usually, due to the large damping produced in the propeller, the vibrations thus produced are not dangerous unless they occur at the normal operating speed of the propeller. However, a thorough analysis of the complete propelling drive is advisable, making allowance for the spring constant of the electric coupling, to avoid any possibility of trouble.

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## Discussion

Discussions will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

# Enclosed Spark Gaps

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**Synopsis:** Ionizing radiation has been discovered to be present in spark gaps of the type commonly used in commercial lightning arresters for the last 15 years. This radiation is emitted from discharges near the insulator-electrode contacts, when impulse voltage is applied to the gap. Ionization is produced by the absorption of this radiation in the spark gap. This effectively reduces the time lag of breakdown. The presence of this radiation explains why higher impulse breakdown voltages are obtained with a sphere gap in the dark than with a lightning-arrester spark gap with porcelain spacer. The radiation effect observed here is similar to that investigated by Wynn-Williams in the three-point gap. This paper tells of experiments performed to determine the reason for the low impulse ratios observed with rutile-spacer spark gaps. The results of this study explain the reason for the low impulse ratio of the "quench gap" and the "ionization gap" utilized in lightning arresters. This new information aids in understanding why low impulse ratios are obtained in high-voltage lightning-arrester spark gaps.

THIS PAPER describes experimental work which revealed a hitherto unrecognized, important factor responsible for the low impulse breakdown voltage found for short enclosed spark gaps such as are commonly used in lightning arresters. To obtain a low impulse ratio it has long been known that some form of ionizing radiation must be present.[1-4] In lightning-arrester spark gaps this radiation is emitted from subsidiary discharges discovered to exist between the electrodes and the insulating spacer, accompanying the dielectric displacement current. The intensity of this radiation may be expected to be proportional to the dielectric displacement current so that spark gaps with spacers of higher-dielectric-constant material, such as rutile,* give lower impulse ratios. This paper describes experiments made to study the interesting breakdown results obtained with rutile-spacer gaps. These tests led to the view that in lightning-arrester spark gaps the spark lag is reduced by radiation emitted from the region of the contact junctions between the insulator and metal electrode. Practical application of this work has been made in the design of lightning-arrester spark gaps by utilizing common insulating materials with intensified radiation means.

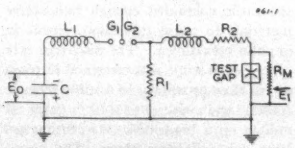



**Figure 1. Impulse test circuit**

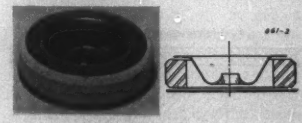
C—One-fourth-microfarad capacitor
$E_0$—60,000 volts direct current
$L_1$—140 microhenries
$L_2$—75 microhenries
$R_1$—400 ohms
$R_2$—25 ohms
$R_M$—Resistance potentiometer
$G_1$, $G_2$—Synchronizing gaps
$E_1$—Voltage for oscillograph plates

## Electrical Tests

The test circuit of figure 1 is commonly used for impulse tests on spark gaps. A capacitor bank, $C$, is charged to 60 kv, just below the breakdown potential of the double gap, $G_1$, $G_2$. The breakdown of $G_1$, $G_2$, is synchronized with the measuring circuits by means of a timed impulse applied to the middle electrode. The rate of increase of voltage over the test gap is determined by the circuit constants $C$, $L_1$, and $R_1$. After the breakdown $L_2$ and $R_2$ assist in regulating the magnitude and wave shape of the surge current. Breakdown potentials are reduced by a tapped noninductive resistor, $R_m$, for voltage measurements by a cathode-ray oscillograph. All impulse breakdowns were made on a front-of-wave-test in which the surge increased at the average rate of 50 kv per microsecond. This rate of rise is recommended by AIEE Standards No. 28 for arresters of six-kilovolt and under rating. Sixty-cycle breakdown tests were taken with a testing transformer having a calibrated third winding and an induction regulator in the low-voltage winding. In approaching the breakdown voltage the rate of increase of 60-cycle voltages controlled by the regulator is reduced so that if the breakdown lag is long, the time of voltage application is also comparatively long. Experiments have shown a small dependence of the 60-cycle breakdown upon radiation, particularly with polished electrode gaps. However, for the purpose of this paper comparisons are based on the measured 60-cycle breakdown values rather than the true d-c breakdown which is more difficult to obtain.

The procedure in testing a gap was to record eight impulse-breakdown tests at ten-second intervals immediately followed by eight 60-cycle breakdown measurements taken consecutively. The average impulse-breakdown value divided by the average 60-cycle crest breakdown determines the impulse ratio. The impulse ratio is used to compare gaps because of its lesser dependence on small differences in gap spacing. A rough indication of the accuracy on repetition of a gap is obtained by expressing in per cent the lowest and highest readings in the series of eight breakdowns as a fraction of the average value. The column in table I under the heading maximum and minimum consistency compares the various gaps in this way.

A typical enclosed spark gap, figure 2, has a disk and a shaped brass electrode separated by an insulating-ring spacer which completely surrounds the sparking regions. The breakdown characteristics of this gap with the porcelain spacer are listed in table I, line *A*. When rutile ceramic was substituted for porcelain as the spacer material, the breakdown values measured are given in table I, line *B*. The main value of the rutile spacer previously anticipated was an improvement in voltage distribution over individual gaps in a multigap arrester. The lower im-



(A) (B)

**Figure 2. Typical spark gap with porcelain spacer and metal electrodes**

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The author is indebted to Doctor Joseph Slepian for many suggestions and guidance of this work. Messrs. Strausser, A. Keto, and R. P. Shimp aided in the early experimental work. Doctor M. E. Bell helped in the preparation of rutile-ceramic spacers. In particular, M. J. Kofoid contributed valuable assistance in the experimental tests and in the preparation of this paper. The co-operation of A. M. Opsahl, F. B. Johnson, and W. G. Roman, of lightning-arrester engineering group, was very helpful and is appreciated.

* One common mineral form of titanium dioxide.

1. For all numbered references, see list at end of paper.

Table I. Average Breakdown Characteristics of Enclosed Spark Gaps With Disk and Shaped Electrodes of Figure 2

| Line | Spacer | Total Number of Tests | Average Impulse Breakdown | 60-Cycle Average Breakdown | Impulse Ratio | Per Cent Consistency | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Impulse | | 60 Cycle | |
| | | | | | | Max. | Min. | Max. | Min. |
| *A* | Plain porcelain | 120 | 13.0 | 7.5 | 1.75 | 114 | 81 | 103 | 95 |
| *B* | Rutile ceramic | 152 | 9.2 | 8.2 | 1.12 | 102.5 | 97.5 | 101.5 | 97 |
| *C* | Leaded porcelain | 128 | 9.5 | 7.7 | 1.23 | 108 | 93 | 102 | 95 |
| *D* | $1.65 \times 10^{-6}$ g radium, plain porcelain | 8 | 8.85 | 7.35 | 1.20 | 105 | 95 | 100 | 98 |

pulse breakdown obtained with rutile-spacer gaps was so surprising that an investigation was made of this phenomenon.

## Rutile

Rutile is a common mineral and is one of the three crystalline forms of titanium dioxide. Powdered rutile can be molded and fired with or without the addition of bonding materials such as china clay. The important difference between rutile ceramic and porcelain is the high dielectric constant of the rutile ceramic. A dielectric constant of 80 to 100 has been measured for rutile ceramics used as spacer materials. Rutile retains its high dielectric constant at frequencies of $10^8$ cycles per second.

Electrical discharges appeared at the spacer-electrode contacts during the breakdown tests. This contact voltage is illustrated in figure 3 where under similar conditions higher gradients exist over the air space when a rutile spacer is used. When highly conducting metal films were placed over the rutile spacer-electrode contact areas no change in impulse ratio resulted. Metal films on porcelain spacer contacts lowered the impulse ratio materially as indicated in line *C* of table I.

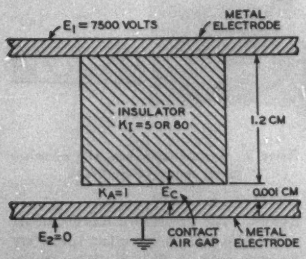


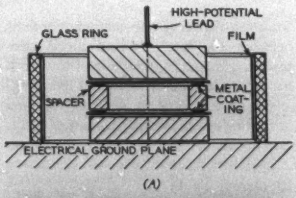

Figure 3. High gradients on assumed-contact air gap with porcelain and rutile spacers

| Insulator | $K_I$(SIC) | $E_c$(Volts) | Gradient(Kv/Cm) |
|---|---|---|---|
| Porcelain | 5 | 31 | 31 |
| Rutile | 80 | 470 | 470 |

The observed phenomenon with the rutile spacer gaps is similar to the effect of radiations from radium[5,6,7] and ultraviolet radiation[5,8] on the breakdown of spark gaps. Tests were made to see if the rutile contained enough radioactive materials to cause this improvement in impulse breakdown. The discharge rate of an electroscope was measured in room air, in close proximity to a rutile ceramic spacer, and with $1.65 \times 10^{-6}$ gram of radium on a brass disk two centimeters from the collecting plate. The corresponding discharge rates were:

1. Air — 0.025 centimeter per minute
2. Rutile — 0.038 centimeter per minute
3. $1.65 \times 10^{-6}$ grams radium — 150 centimeters per minute

A plain porcelain-spacer gap was tested with the radium-treated disk used in the electroscope tests and found to have a




(A)

(B) (C)

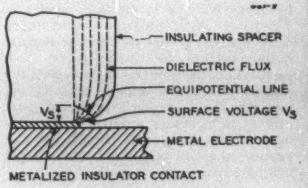
Figure 4. Dark-room tests

low impulse ratio of 1.2, table I, line *D*. It was concluded that the radioactive impurities in the rutile do not exist in sufficient quantities to cause the observed phenomena.

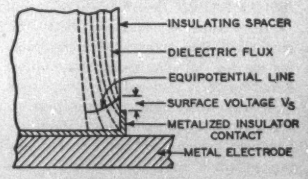
The possibility of the insulating surface emitting a radiation when electrically stressed was suggested and tests were made to see if such radiations were present. A rutile ceramic spacer with sprayed lead contacts was dipped into hot liquid ceresin wax, then cooled so that the entire surface of the spacer was coated with wax. The lead contacts on the rutile spacer were then scraped to remove the wax enough to make good contacts with the metal electrodes. In this scraping it is probable that some of the high-dielectric-constant spacer was exposed in the contact region. A low impulse ratio was obtained with the spacer insulating surfaces covered with ceresin wax. It, therefore, seems improbable that radiation from a stressed insulating surface causes the observed effect.

## Barrier Tests

An attempt was made to interpose a barrier between the spacer-electrode junc-




(A) RECESSED CONTACT




(B) OVERLAPPED CONTACT

Figure 5. Potential over insulator surface near metalized contacts

tion and the central sparking region, by placing a loose fish-paper cylinder within the spark gap. At first low impulse voltages were obtained, but after changing the paper cylinder to a telescope construction, which was really light-tight, a high impulse ratio was obtained. When a $^1/_{64}$-inch-diameter hole was drilled through the otherwise opaque barrier, the impulse ratio was lowered.

Additional tests were made with picein wax covering the rutile spacer-electrode contact junctions on the inside of the spacer. When both of the electrode-insulator contact regions were covered with wax, high impulse ratios resulted. With only one contact region waxed, low impulse ratios were obtained. A contact layer of sprayed metal was brought up the inside of the rutile spacer and the con-

tact regions waxed but with a small ring of exposed lead extending beyond the wax. Tests showed low impulse ratios when the lead film was exposed.

## Dark-Room Tests

A bare X-ray film was located around a rutile spacer with sprayed lead contacts and two disk electrodes as shown in figure 4A. No blackening appeared when this

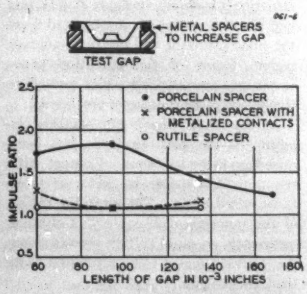



**Figure 6. Variation in impulse ratio obtained by increasing gap distance while maintaining constant dielectric thickness**

gap was energized at 7,500 volts, 60-cycle frequency, for several hours. One hundred short-time chopped surge waves of ten kilovolts crest gave no trace of radiation on the film. When the gap of figure 4A was excited to 8,000 volts crest at 540 kilocycles for one hour the X-ray film obtained is reproduced in figure 4B. The whole film was diffusely blackened but two intensely blackened lines appeared as a result of radiation from the contacts. A picture of the contact discharges was made with Zeiss camera (approximately f5) with a two-minute exposure in a dark room using the fastest available commercial film. The contact discharges were greatly amplified by increasing the voltage to just under the insulator flashover value. The picture in figure 4C shows some indication of the localized nature of the contact discharges. One flashover took place during the exposure and is visible in the picture. The two bands of light in the picture are the result of several points of light from contact discharges

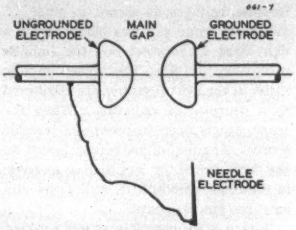



**Figure 7. Three-point spark gap**

that wandered around irregularly on the periphery of the rutile spacer at the lead-sprayed film outside edges.

## Radiation From Contact Discharges

It is now obvious that the lower impulse-breakdown values obtained by the use of rutile spacers are due to a radiation in the gap coming from localized electric discharges at or near the inside contact junctions of the insulator and electrode. The radiation is present in abundant quantities to produce the effect through a $^1/_{64}$-inch-diameter hole. The discharges are attributed to stress concentrations and are present with highly conducting metal contact films. Two ways of producing stress concentrations with typical spacer shapes are shown in figure 5. It is not necessary to postulate imperfections in the surface of the dielectric to explain high air gradients. A metal contact film on the rutile spacer reduced the visible radiation intensity so that the contact discharges could not be seen in a dark room with careful observation under normal gap stress. Under this reduced visible intensity the impulse ratio was

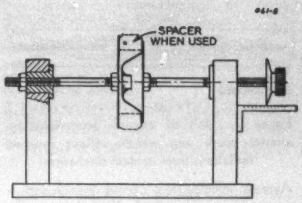



**Figure 8. Externally supported spark gaps**

equally low. In the case of porcelain spacers the lead contact films definitely lowered the impulse ratio. This is attributed to the more favorable location of the radiation source on the porcelain.

That porcelain spacers may be made to radiate with greater intensity so as to lower still further the impulse ratio was proved by testing the porcelain gap at increased gap spacings which effectively increased the working stress of the porcelain. In the curves of figure 6 are plotted the impulse ratio as a function of the gap spacing where the gap spacing was increased by the addition of metal-ring spacers on top of the various insulating spacers. At about three times the normal gradient the plain porcelain spacer gap has an impulse ratio of 1.2.

## The Three-Point Spark Gap

The impulse breakdown potential of a spark gap can be lowered by the three-point effect first explained by C. E. Wynn-Williams[9] in 1926. A typical three-point gap is reproduced in figure 7. When the sharp point of the needle was placed within six centimeters of the ungrounded electrode and electrically connected to it so that it was "visible" to the gap, a lower surge breakdown voltage was obtained. All barriers when placed in front of the point neutralized this effect except a specially prepared thin celluloid film. The effect was obtained in a dark room where no discharge could be seen to pass

**Table II. Tests With Electrodes Supported Externally—Figure 8**

| Spacer | Electrodes | Gap (Mm) | Surge Breakdown (Kv) | 60-Cycle Breakdown (Kv) | Impulse Ratio | Average Surge Gradient (Kv/Cm) | Average 60-Cycle Gradient (Kv/Cm) |
|---|---|---|---|---|---|---|---|
| None—open to room | Brass disk and shaped | 1.65 | 14.5 | 8.84 | 1.64 | 88 | 53.5 |
| None—in light-tight box | | 1.65 | 17.6 | 9.42 | 1.87 | 107 | 57.0 |
| Plain porcelain | | 1.65 | 13.2 | 7.68 | 1.72 | 80 | 46.5 |
| Leaded-contact porcelain | | 1.90 | 10.8 | 7.93 | 1.36 | 57 | 41.7 |
| Leaded-contact rutile | | 2.11 | 9.08 | 8.48 | 1.07 | 43 | 40.2 |
| None—open to room | 3.8-cm brass* polished spheres | 1.65 | 14.5 | 9.04 | 1.50 | 88 | 58.3 |
| None—in light-tight box | | 1.65 | 24.4 | 9.29 | 2.63 | 148 | 56.3 |

* One hour between polishing and testing.

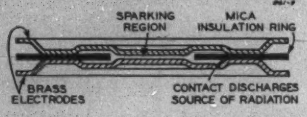



**Figure 9. Unit of quench gap, lightning-arrester spark gap which utilizes ionizing radiations from contact discharges**

Average impulse ratio of unit quench gap = 1.05

from the needle point to an electrode. His conclusions were that:

"1. Before the three-point phenomenon can be obtained some form of discharge, silent or spark, must be 'visible' from the main gap and within a certain distance of it.

"2. The phenomenon is obtained in the absence of:

"(*a*). Disturbance of the electric field near the main gap and

"(*b*). The passage of ions from the pilot discharge into the main gap.

"3. A radiation is emitted by the pilot discharge which can ionize the gas in the main gap.

"4. When this radiation is prevented from reaching the main gap the usual three-point effect is not obtained.

"5. The three-point effect is still produced when the electrodes are so shielded as to prevent any photoelectric effects...

"6. The observed properties of this radiation seem to establish the limits of its wave length as being approximately 13 to 1,000 angstroms, and they coincide to a large extent with the corresponding properties of *entladungstrahlen*."

As these conclusions so thoroughly explain the rutile-spacer spark-gap tests, it seems safe to conclude the same phenomena must be present in both cases.

## Recent Work

H. Rather[10] has measured the absorption coefficient of similar radiation from a spark discharge. He believes the gas-ionizing radiation to be between the limits of 800 to 1,000 angstroms. By means of a Wilson cloud-chamber apparatus he has measured and extrapolated the absorption coefficient of the effective radiation from sparks to be $\mu=2$ for air, $\mu=0.8$ for hydrogen, and $\mu=5$ for oxygen, at 760-millimeter pressure.

## Mounted-Electrode Tests

To observe the performance of a gap without short insulating spacers the disk and shaped electrodes were mounted on an adjustable micrometer spark gap as shown in figure 8. The electrode sparking surfaces were first polished, cleaned, and then roughened with fine alundum paper. The roughening process was repeated before each set of tests. The gap spacing was set equal to that of the porcelain gap of figure 2, and tested with the electrodes open to room air. The impulse ratio measured was 1.64 with 60-cycle and impulse voltages as shown in table II. When the same gap was placed inside a light-tight maplewood box the impulse ratio rose to 1.87. The higher impulse ratios in the light-tight box are attributed to a decrease of radiation. When the spark gap is open to room air, possible sources of radiation are corona points on the surge generator, radioactive material in the room, atmospheric radiations, and incandescent filaments.

With a plain porcelain spacer inserted between the electrodes of figure 8, the impulse ratio measured was 1.72. As the porcelain spacer makes the gap relatively light-tight some radiation must be present normally in the plain porcelain gap. The lower breakdown gradients recorded in table II for this test are added evidence of radiation. When a sprayed-lead porcelain spacer was tested in the same gap structure the impulse ratio was 1.36. This low value is attributed to a more favorable location of the radiation present in the porcelain-spacer gap. A leaded rutile spacer in the same gap structure gave an impulse ratio of 1.07. The breakdown gradients are low, indicating a greatly increased intensity of radiation.

Two 3.8-centimeter spherical electrodes were mounted in the micrometer support and tested open to the room and in the dark box. The results listed in table II show a similar increase in impulse ratio for spherical electrodes in the light-tight box.

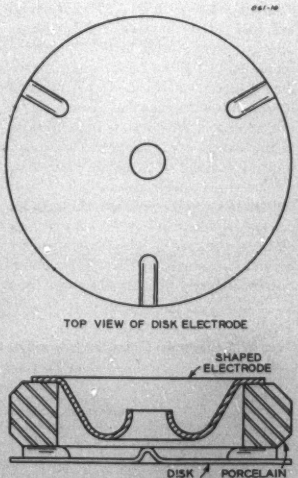



**Figure 10. "Ionization" gap**

Average impulse ratio of single ionization gap = 1.2

## Applications

A single unit of the "quench gap" construction[11] is shown in figure 9. In this gap effective radiations are emitted from the mica insulator and electrode-contact region. Some of this radiation penetrates into the sparking region and effectively lowers the time lag of breakdown.

In the "ionization" gap sketched in figure 10 the disk electrode has been raised in three locations. Contact with the porcelain spacer is made on these three raised lands. The air in the region of the porcelain-disk contact is stressed sufficiently on rapid voltage rises to cause the sparking region to be irradiated as in the "quench gap."

## Conclusions

The impulse ratio of spark gaps with spacings of between one and two millimeters depends upon the radiation present in the gap. An effective radiation is present in the usual porcelain-enclosed gap used in lightning arresters. This radiation is emitted from electrical discharges at the insulator-electrode junctions. A high-dielectric-constant spacer gives low impulse ratios, probably because the intensity of the effective radiation is proportional to the displacement current in the insulator. The wave length of the most effective part of a similar radiation was determined by Wynn-Williams in a study of the three-point spark gap as lying between 13 and 1,000 angstroms. Experiments in this region of the soft X-ray spectrum are difficult due to rapid air absorption.

The discovery of this radiation in porcelain-enclosed spark gaps explains why porcelain space gaps have lower impulse ratios than plain spark gaps of the same spacing in the dark. The results of this study fully explain the reasons for the low impulse ratios obtained in the "quench gap" and the "ionizing gap" which are both utilized in commercial lightning arresters.

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# Water Solution in High-Voltage Dielectric Liquids

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IT HAS long been recognized by the practical engineer responsible for the proper maintenance of high-voltage oil-filled electrical equipment that water constitutes one of the chief and in some instances the only serious threat to successful service. However, consideration of the dangers presented by water during the operation of high-voltage machines must not be limited to a study of the relation between the dielectric strength and the water content of the insulating liquid used. For successful operation, the cellulosic insulation must be maintained in a dry condition. Water in such dielectrics leads ultimately to insulation failure. One of the first lines of defense against this disastrous result is the adequate drying of the solid dielectric in the factory manufacture of the equipment. Just as important, however, is the clear recognition that cellulosic insulation may be brought to a hazardous condition in service by water absorption from the surrounding atmosphere through the insulating liquid. The sorption of moisture by cellulosic insulation in this manner is of importance to all types of liquid-treated electrical apparatus but is of especial importance to liquid-cooled transformers in which the circulation of the liquid, carefully factored into the design for cooling purposes, so effectively presents a continuous supply of dissolved moisture to the hygroscopic insulation of the windings.

The dielectric-strength test of insulating liquids has long been accepted as an adequate protection against dielectric deterioration produced by water, but such a test as used in practice gives no adequate protection against the insidious penetration of water and its sorption by the cellulosic insulation. The practical dielectric strength represents the summation of many deteriorating effects, including the effect of fibers, dust, and other suspended or dissolved materials. The effect of these materials becomes greatly pronounced in the presence of water[1-4] and their prevalence in normal commercial practice has necessitated the establishment of dielectric-strength standards of such value that dissolved moisture may unsuspectedly be present in an amount which, because of its continuous transfer to the liquid-immersed cellulose insulation, may be sufficiently large seriously to affect the insulating properties of the latter and to present a dangerous condition for commercial use.

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1. For all numbered references, see list at end of paper.

## A Laboratory Test for Quantitatively Determining the Amount of Dissolved Water in Insulating Liquids

A number of test methods have been suggested for quantitatively determining the amount of water dissolved in mineral oil and other organic liquids.[5] The method adopted in this study has been a modification of the procedure suggested by Smith and Bryant,[6] the water content being expressed in parts per million by weight.

Dry nitrogen gas is bubbled through 500 to 1,000 grams of the carefully weighed insulating liquid at 130 degrees centigrade for a period of three hours. From the insulating liquid the nitrogen gas is led through two liquid-air traps where the entrained moisture is removed. The frozen condensate in the traps is dissolved in 25 cubic centimeters of dry acetone and slowly added to a cold acetyl chloride-pyridine mixture. In the preparation of this mixture, 10 cubic centimeters of acetyl chloride dissolved in dry benzene (118 grams per liter of solution) are contained in a dry 250-cubic centimeter glass-stoppered flask and cooled in an ice bath. Two cubic centimeters of dry pyridine are added dropwise to the acetyl chloride solution with continual shaking. A white precipitate of acetyl chloride-pyridine complex is formed.

After the slow addition of the acetone condensate solution to the ice-cold acetyl chloride-pyridine complex has been completed, the mixture is removed from the ice bath and allowed to stand at room temperature in diffused light (not in direct sunlight) for at least 15 minutes, but not more than 30 minutes, after which 20 cubic centimeters of dry ethyl alcohol are slowly added with continuous shaking. After a further standing at room temperature for five minutes, the solution is ready for titration with 0.5 *N* sodium hydroxide solution using phenolphthalein indicator.

A blank run is made simultaneously with the sample, using completely duplicate conditions except that no frozen distillate is added. This allows correction to be made for errors due to moisture inadvertently present.

In the actual application of water-testing procedures for insulating liquids, mineral oil is one of the more important insulating liquids tested. As is well

2. UEBER EINEN EINFLUSS DES ULTRAVIOLETTEN LICHTES AUF DIE ELEKTRISCHE ENTLADUNG, Hertz. *Wied. Ann.*, volume 31, 1887, pages 983-1000.

3. INCONSTANZ DES FUNKENPOTENZIALES, Jauman. *Wied. Ann.*, volume 55, 1895, pages 656-83.

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5. QUECKSILBER LAMPE UND RADIUM ALS VORIONISATOREN IHR EINFLUSS AUF DEN ELEKTRISCHEN FUNKEN, W. Rogowski and R. Tamm. *Archiv. f. Elektrot*, volume 20, 1928, pages 107-14.

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7. RADIUM IMPROVES OPERATION OF SPARK GAPS, W. E. Berkey. *Electric Journal*, volume 31, 1934, pages 101-03.

8. EFFECT OF ULTRAVIOLET ON BREAKDOWN VOLTAGE, G. Nord. AIEE TRANSACTIONS, volum 54, 1935, pages 955-8.

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11. CHARACTERISTICS OF THE NEW STATION-TYPE AUTOVALVR LIGHTNING ARRESTER, W. G. Roman. AIEE TRANSACTIONS, volume 56, 1937, pages 819-22.

## Discussion

Discussion will be found in the 1940 annual TRANSACTIONS volume and in the 1940 "Transactions Supplement" to ELECTRICAL ENGINEERING.

known, this material will be found in commercial apparatus in all stages of oxidation. This oxidation results in the formation of volatile acidic materials. Such products entrapped in the refrigerated tubes of the water-testing apparatus, will in themselves react with acetyl chloride or the sodium hydroxide used for the titration and produce erroneous results. For mineral transformer oils in normally good condition, the correction factor is negligible but for oils in the higher stages of oxidation a correction in the water content value must be applied. This correction corresponds to 7.3 parts per million of water content for each 1.0 milligram of potassium hydroxide per gram of oil used in the acidity titration.

## The Solubility of Water in Dielectric Liquids

The amount of water dissolved by a liquid is a function of the chemical nature of the liquid itself and the conditions to which it is exposed. In the case of mineral insulating oil, the degree of refining and the previous oxidation to which it has been subjected are factors of real importance. Figure 1 illustrates the effect of refining treatment on the solubility

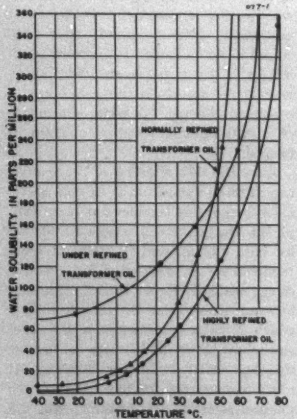

WATER SOLUBILITY IN PARTS PER MILLION
NORMALLY REFINED TRANSFORMER OIL
UNDER REFINED TRANSFORMER OIL
HIGHLY REFINED TRANSFORMER OIL
TEMPERATURE °C.

**Figure 1. The solubility of water in mineral transformer oil and the effect of the refining treatment**

of water in mineral transformer oils of low cold test.

In the use of mineral oils, oxidation effects must not be ignored when water-solubility problems are considered. Oxidation promotes the emulsification of water and leads to increased water solubility in the oil. Unless otherwise stated, only new, unoxidized mineral oils are used throughout this paper.

Synthetic, noninflammable, dielectric transformer liquids in commercial use are the chlorinated derivatives of the benzenoid hydrocarbons. These compounds are characterized by a high resistance to oxidation and are, therefore, not susceptible to changes in water solubility during use. This fact is demonstrated in the data of figure 2 which describe the solubility of water in new and used Pyranol.

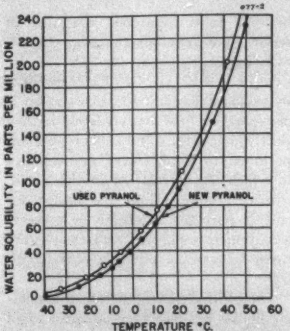



**Figure 2. The solubility of water in transformer Pyranol**

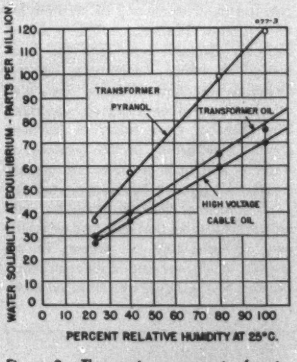

WATER SOLUBILITY AT EQUILIBRIUM - PARTS PER MILLION
TRANSFORMER PYRANOL
TRANSFORMER OIL
HIGH VOLTAGE CABLE OIL
PERCENT RELATIVE HUMIDITY AT 25°C.

**Figure 3. The maximum amount of water absorbed by transformer and cable insulating liquids exposed to humid air**

## The Hygroscopicity of Dielectric Liquids

The data presented in figures 1 and 2 are of interest and importance in indicating the limiting values of solubility beyond which water cannot accumulate in the liquid without visible cloud formation. Such values, however, give no indication of the sorptive ability of the liquid when exposed to less than water saturated atmospheres as in normal handling and use.

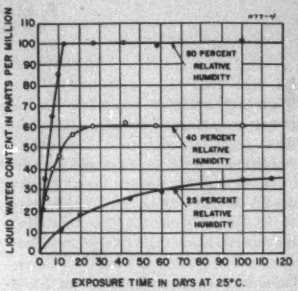

LIQUID WATER CONTENT IN PARTS PER MILLION
80 PERCENT RELATIVE HUMIDITY
40 PERCENT RELATIVE HUMIDITY
25 PERCENT RELATIVE HUMIDITY
EXPOSURE TIME IN DAYS AT 25°C.

**Figure 4. The absorption of water from humid air by transformer Pyranol**

Figure 3 illustrates the water solubility in transformer liquids at equilibrium with air, the water content of which is expressed in the commonly used terms of relative humidity. Figure 3 also compares the water sorptive characteristics of a typical, American, Pirelli-type, high-voltage mineral cable oil. The comparative Saybolt Universal viscosity values at 37.8 degrees centigrade for the three liquids are:

| | |
|---|---|
| Transformer Pyranol | 55 seconds |
| Transformer mineral oil | 58 seconds |
| Pirelli cable oil | 100 seconds |

The water equilibrium set up by an insulating liquid and the air with which it may be in contact is of importance in many commercial uses. In the handling of insulating liquids, however, it is also important to know the rate at which water is taken up by liquid. This is an extremely difficult practical problem since the speed with which a liquid approaches its water equilibrium condition is dependent on a large number of empirical factors, prominent among which is the intimacy of contact between the liquid and the humid atmosphere from which the water is taken. Large surface exposure produced by liquid circulation or other means accelerates water absorption. Figures 4 and 5 illustrate the rate of water absorption for mineral transformer oil and for transformer Pyranol exposed to air of different humidities. In this work the liquids were exposed in a

quiescent state under the following conditions:

Volume of liquid, 7,500 cubic centimeters
Surface area exposed, 375 square centimeters
Liquid depth, 20 centimeters
Temperature of exposure, 25 degrees centigrade

The rate at which water is taken up by mineral oil is but little affected by those

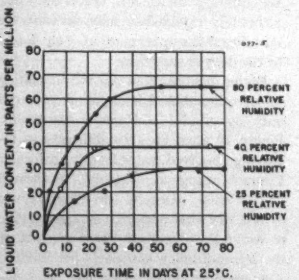

LIQUID WATER CONTENT IN PARTS PER MILLION
80 PERCENT RELATIVE HUMIDITY
40 PERCENT RELATIVE HUMIDITY
25 PERCENT RELATIVE HUMIDITY
EXPOSURE TIME IN DAYS AT 25°C.

**Figure 5. The absorption of water from humid air by mineral transformer oil**

duces the water content of the latter. The rate at which the water is transferred from wet oil to the dry cellulose depends on factors similar to those which apply in the transfer of water from humid air to dry oil. Chief among these is the intimacy of contact between the cellulose fiber and the oil. Factors causing oil circulation, thus bringing a continuous supply of wet oil into contact with the paper insulation of a typical transformer-coil winding, will accelerate the moisture removal from the oil. Figure 7 illustrates the water transfer for one specific setup in which the dried cellulosic insulation was immersed in wet transformer liquid maintained without circulation at 25 degrees centigrade.

The data of figure 7 were obtained by humidifying the transformer liquid at 25 degrees centigrade. Kraft insulating paper (0.001 inch) was dried at 110 degrees centigrade under a pressure of 0.3 millimeter of mercury for 24 hours. The dry paper weighed 40 grams and was in the form of a cylindrical tube. The vacuum-dried paper, approximately 15 square feet in area, was immersed in 1 1/2 quarts of the wet liquid contained in a two-quart sealed, glass container which was allowed to stand without agitation. Samples of the liquid were withdrawn at frequent intervals for measurement of the dissolved water content.

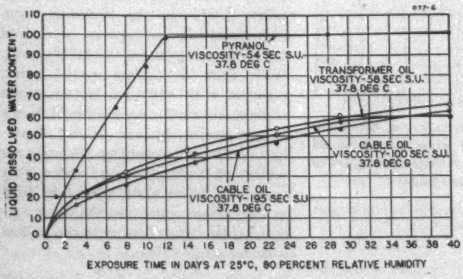

LIQUID DISSOLVED WATER CONTENT
PYRANOL VISCOSITY-54 SEC S.U. 37.8 DEG C
TRANSFORMER OIL VISCOSITY-58 SEC S.U. 37.8 DEG C
CABLE OIL VISCOSITY-100 SEC S.U. 37.8 DEG C
CABLE OIL VISCOSITY-195 SEC S.U. 37.8 DEG C
EXPOSURE TIME IN DAYS AT 25°C, 80 PERCENT RELATIVE HUMIDITY

**Figure 6. Comparing the water absorption by insulating liquids of different viscosity when exposed to humid air at 25 degrees centigrade**

physical and chemical changes accompanying increased oil viscosity. This is illustrated in the data of figure 6 which compare three mineral oils of the Gulf Coast crude type, with viscosities which range from 58 seconds to 195 seconds Saybolt Universal at 37.8 degrees centigrade.

## The Transmission of Water Through the Insulating Liquid and Its Sorption by the Cellulosic Insulation Immersed Therein

Cellulose has been described as a very hygroscopic material whose ability to absorb water is comparable to even the best of chemical desiccants.[7] It is, therefore, not unexpected to find that dry cellulose immersed in wet oil, re-

Figure 7 is of value in indicating the rapidity with which dry cellulosic insulation will absorb moisture from the wet insulating liquid of a transformer. In obtaining the data of figure 7, it must be emphasized that there was a limited supply of water available that held by the insulating liquid. As the water was removed from the latter, its water content dropped until after about four days for the mineral transformer oil and 16 days for the transformer Pyranol an equilibrium was established between the water-in-liquid and water-in-cellulose condition. This equilibrium was substantially independent of the nature of the insulating liquid.

Figure 8 illustrates the water transfer occurring when wet insulating paper is immersed in dry transformer liquids. These data were obtained during a test run in which 40 grams of paper, prepared by exposure for 48 hours to air at 70 per cent relative humidity, 32 degrees centigrade, were immersed in the shape of a cylindrical tube in 1 1/2 quarts of dry insulating liquid, maintained throughout the test in a sealed container at 25 degrees centigrade. It is obvious from the data of figures 7 and 8 that the direction of water transfer, whether from liquid to cellulose or cellulose to liquid, is dependent on the relative moisture content of the materials involved.

In a sealed container, once the equilibrium condition is reached between the water content of the cellulose and that of the insulating liquid, it cannot be considered in an easily changed condition. This is illustrated in the data of figure 9. Here the 25-degrees-centigrade data of figure 7 for dry paper in wet mineral transformer oil and that of figure 8 for

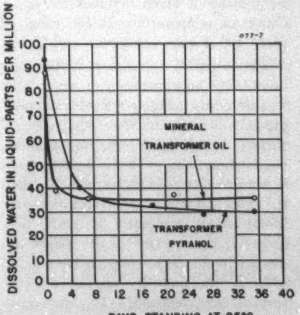



**Figure 7. The dehydration of wet insulating liquids as a result of moisture absorption by dry cellulosic insulation immersed therein**

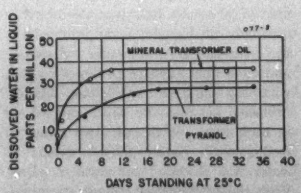



**Figure 8. The absorption of water by dry insulating liquids in contact with cellulosic insulation previously exposed to humid air**

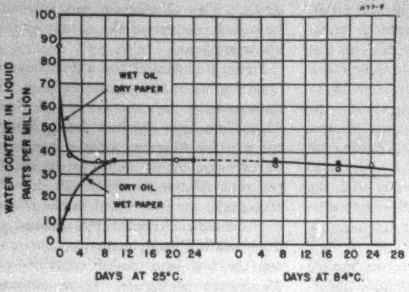



**Figure 9: The characteristics of the moisture equilibrium set up between mineral transformer oil and the impregnated cellulose insulation**

wet paper in dry mineral transformer oil are plotted together. After the common equilibrium has been established, each setup is heated from a 25- to an 84-degree-centigrade liquid temperature. The equilibrium is substantially unchanged. This behavior is of real importance in transformer practice for it indicates the danger which results when moisture is allowed to be dissolved by the insulating liquid. When once the moisture is absorbed by the impregnated cellulose, unless it be present in abnormally large amounts, it is released again only by drastic treatment which involves the application of temperatures in the range of 95 to 100 degrees centigrade and higher.

The practical application of the data describing the absorption of water from wet oil by dry cellulose is made extremely difficult because of the importance of surface contact in determining the final equilibrium value. This is demonstrated in a series of tests in each of which is used the same amount of oil having the same initial water content. In each test, however, the amount of dry paper immersed in the oil is changed both in respect to the quantity present and the surface area exposed. In one setup two grams of vacuum-dried 0.001-inch kraft paper were immersed in the oil so that the total surface area of 1.50 square feet was entirely bathed by the liquid. In a second setup, 40 grams of the same vacuum-dried paper with a total surface area of 30 square feet were assembled in a cylindrical-shaped roll and immersed in the oil so that only the outer roll surface and ends were exposed to direct contact with the oil. An equilibrium was established between the paper and the oil in each case. With only two grams of well-exposed paper, 0.0082 grams of water was absorbed per gram of paper. With the compact roll assembly containing 40 grams of paper, only 0.0014 gram of water was absorbed per gram of paper.

## The Dehydration of Insulating Liquids

In the data already presented, it will be observed that in no instance has the presence of initially dry paper been able

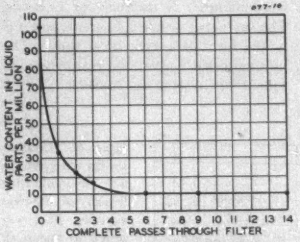



**Figure 10. The dehydration of transformer Pyranol by means of paper filtration at 25 degrees centigrade with frequent changes of the filtering papers**

Used papers were replaced at the time of each test value indicated

to reduce the water content of the dielectric liquid to zero. An equilibrium is ultimately set up which recalls the equilibrium generally recognized to exist between the water content of paper and of air. In the drying of cellulosic insulation, it is necessary to upset this equilibrium which is done in common practice by the use of heat and vacuum. The fact that an equilibrium also exists between water-in-liquid and water-in-cellulose indicates clearly that under some conditions as for example in the data of figure 8, the cellulose may impart water to the liquid. In like manner, an improperly dried blotter paper used in the filter-press treatment of the dielectric liquid, although removing suspended particles, may even lead to an increased oil-dissolved water content. It is further obvious that unless completely dried filter papers are successively supplied in the filtering treatment, the equilibrium ultimately established may prevent the lowering of the water content of the liquid to the desired safe value.

Water in solution in mineral insulating oil or other dielectric liquid is removed only by careful and severe treatment. Figure 10 illustrates the difficulty of removing dissolved water from transformer Pyranol using a standard seven-inch blotter press. Despite the extensive use of new, dry filter papers, it was impossible to lower the dissolved water content of the Pyranol below ten parts per million.

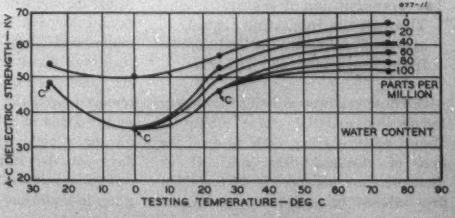
A modified filter press has been designed[8] which incorporates frames much deeper than those of the usual plate and frame press. These deeper frames give spaces which are filled with 80/300-mesh fullers earth. In the standard seven-inch press, sufficient capacity is provided for about one gallon of the fullers earth. With such a "fullers earth" press, equipped with well-dried blotter papers of the usual type, complete liquid drying is more easily obtained. Using 30 gallons of Pyranol containing 116 parts per million of dissolved water, and a filter containing fullers earth previously dried at 200 degrees centigrade, the water content of the Pyranol in parts per million is decreased as follows:

| | |
|---|---|
| Initial water content | 116 |
| After one pass through filter | 9 |
| After one-half hour circulation through the filter | 0 |

It is customary in some instances to

**Figure 11. The rapidly applied a-c dielectric strength of mineral transformer oil as a function of its dissolved and suspended water content and the testing temperature**

Points marked C indicate that the oil contains suspended as well as dissolved water. All dielectric strength tests were taken with a 0.20-inch gap setting



degas mineral oil and other insulating liquids immediately after filter press or centrifuge treatment by passing the material through a vacuum chamber in the form of a thin film or spray. The assumption is usually made that such deaeration rapidly and effectively eliminates the dissolved water. This is not necessarily true. Mineral oil, even to the point where the dissolved air content is reduced to less than one per cent may still retain substantially large amounts of dissolved water. This was demonstrated in one form of commercial degassing equipment using mineral transformer oil containing 70 parts per million of water. After the degassing treatment, the oil still contained 46 parts per million of dissolved water.

## A Practical Method for the Quantitative Estimation of Dissolved Water

A simple method for estimating the amount of water in solution in an insulating liquid involves the determination of its cloud point. Carefully carried out, the cloud point indicates that temperature below which the water in solution exceeds the saturation value of the liquid and separates with the formation of faint cloud. This water separation becomes pronounced and forms a turbid suspension in the liquid as the temperature is further lowered. This test procedure is limited to those materials free or substantially free from wax so that the formation of a cloud due to wax separation is avoided in the range of temperature of interest in dissolved-water determinations. Since, in general, the dielectric liquids in common use are of the naphthenic type of mineral oil or are synthetic benzenoid compounds free from wax separation on cooling, this limitation is not of serious significance.

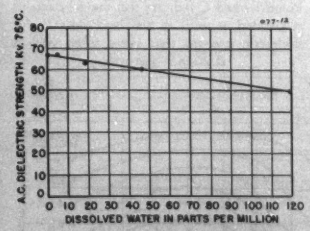



**Figure 12. The effect of dissolved water on the rapidly applied a-c dielectric strength of mineral transformer oil tested at 75 degrees centigrade**

All dielectric strength tests were taken with a 0.20-inch gap setting

The cloud-formation temperature relation to the liquid dissolved-water content is obtained from figure 1 for mineral transformer oil and from figure 2 for transformer Pyranol. The dissolved-water contents shown in these figures are those of the water-saturated condition for the corresponding temperatures. These temperatures are, therefore, the cloud-point values since further increase in water content or a further decrease in temperature results in the formation of a visible cloud.

The difficulty in the cloud-point test is that, except for the highest water contents, the test involves refrigeration with accompanying frost formation on the walls of the containing vessel and the necessity of protecting the liquid under test from water pick up due to frost formation on its surface. A suggested form of test apparatus utilizes a clear vacuum bottle within which the liquid under test, contained in a clear-glass stoppered tube, is cooled at a standardized rate in accordance with principles of the method of test for the cloud and pour point of mineral oils, described under designation *D*97-34 of the American Society for Testing Materials.

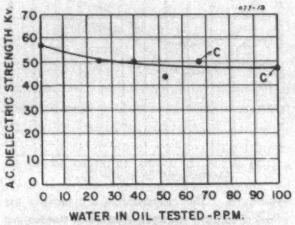



**Figure 13. The rapidly applied a-c dielectric strength for mineral transformer oil tested at 25 degrees centigrade as a function of its dissolved and suspended water content**

Points marked C indicate that the oil contains suspended as well as dissolved water. All dielectric strength tests were taken with a 0.20-inch gap setting

## The Effect of Dissolved Water on the A-C Dielectric Strength of Insulating Liquids

Repeated researches have indicated that the dangerously low dielectric strengths normally attributed to the presence of water in commercial insulating liquids are to be associated as well with the accidental presence of suspended solids such as dust particles, fibers, and the like.[1-4] It is undoubtedly true that mineral oil or other insulating liquid may contain appreciable amounts of dissolved water and, in the absence of suspended impurities, still retain what is commercially regarded as a good dielectric strength. This results in the fact, already indicated, that the dielectric-strength test as commercially applied does not give good protection against the insidious penetration of moisture through the liquid to the hygroscopic cellulosic insulation immersed therein. Irrespective of its effect on the dielectric properties of the liquid, unlimited penetration of moisture and its sorption by the cellulose must be avoided if satisfactory commercial operation of high-voltage apparatus is to be obtained.

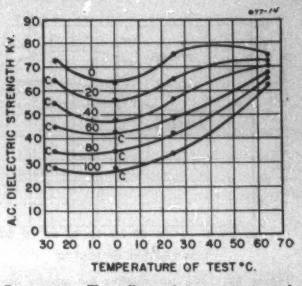



**Figure 14. The effect of temperature and dissolved and suspended water in the a-c rapid applied dielectric strength of transformer Pyranol**

Points marked C indicate that the oil contains suspended as well as dissolved water. The figures on the curves indicate the total water content of the liquid. All dielectric strength tests were taken with a 0.20-inch gap setting

Because of the unavoidable variation in water content during the handling and testing of an insulating liquid, it has been most convenient to determine the dielectric strength of the liquid for at least four water-content values covering the range of interest and from the smooth line (average) relation established, to select definite values of water content for comparison and further technical analysis. Thus, for example, the 75-degree-centigrade data of figure 11 are based on the smooth-line relation of figure 12 which describes the dielectric strength of mineral transformer oil at 75 degrees centigrade as a function of its dissolved-water content, the values indicated being experimentally determined. In general, the basic experimental data correlating the dielectric strength and the water content of the insulating

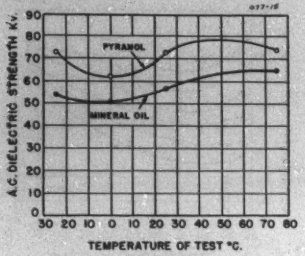



**Figure 15. The comparative a-c rapidly applied dielectric strength of dry transformer Pyranol and dry mineral transformer oil**

All dielectric strength tests were taken with a 0.20-inch gap setting

liquid are eliminated for reasons of brevity. The analyses which are shown are based on selected points taken from the smooth-line relation correlating the experimentally determined values.

The dielectric test results were obtained using brass electrodes meeting the requirements of the American Society for Testing Materials, designation *D*117-33. The gap distance used throughout was 0.20 inch. Temperatures recorded are the liquid temperature values at the time of test. In all instances, no dielectric-strength readings were made until the liquid had been at the testing temperature for several hours. The water-content values given include suspended as well as liquid dissolved moisture. The presence of suspended water is indicated.

The rapidly applied dielectric strength has been determined in accordance with American Society for Testing Materials, designation *D*117-36, in which the voltage is evenly raised to breakdown at the rate of three kilovolts per second.

To define adequately the effect of dissolved and suspended water on the dielectric strength of an insulating liquid, it becomes evident at once that the temperature of test must be carefully specified. Practically speaking, a wide range of testing temperatures must be covered for liquid treated insulations are often used in high-voltage dielectric practice specifically because of the stability of their dielectric properties over a wide range of operating temperatures. In these tests, temperatures from −25 to +75 degrees centigrade have been studied.

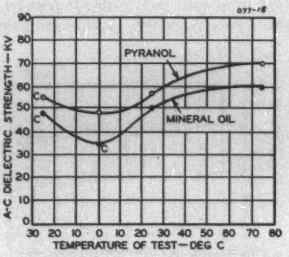



**Figure 16. The comparative a-c rapidly applied dielectric strength of mineral transformer oil and transformer Pyranol, each containing 40 parts per million of dissolved water**

Points marked C indicate that the oil contains suspended as well as dissolved water. All dielectric strength tests were taken with a 0.20-inch gap setting

It has been pointed out in a previous publication[9] that the dielectric strength of mineral insulating oil as affected by temperature varies from oil to oil. With some oils, notably the viscous cable oils, the dielectric strength falls with temperature increase above room temperature. With mineral oils of the transformer type, the dielectric strength increases to a maximum with temperature increase above room temperature. The dielectric strength-temperature relation has been considered to reflect the solubility characteristics of dissolved air. In this study of the dielectric strength of mineral oil as affected by the dissolved and suspended water content, available data are limited to the behavior of air-saturated mineral transformer oil prepared from Gulf Coast crude and having a viscosity at 37.8 degrees centigrade of approximately 58 seconds Saybolt Universal. With such an oil, the effect of temperature increase on the dielectric strength is a function of its water content. The dielectric strength increases most rapidly with temperature increase from 25 to 75 degrees centigrade when the water content of the oil is held at low value. This is illustrated in the data of figure 11.

In any study of the effect of water on the dielectric strength of mineral oil, difficulty is at once experienced because of water separation as the temperature is lowered. This limits the study of the effect of dissolved water to a narrow range of water contents as the lower temperatures are investigated. Thus, as is shown in figure 12, even with a water content as large as 120 parts per million, clear solutions are obtained at 75 degrees centigrade and the decrease in dielectric strength with increased water content is easily demonstrated. At 25 degrees centigrade, however, the limit of water solubility as indicated in figure 1 for

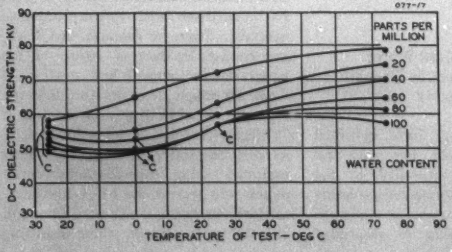



**Figure 17. The rapidly applied direct-voltage dielectric strength of mineral transformer oil as affected by tem perature and its dissolved and suspended water content**

Points marked C indicate that the oil contains suspended as well as dissolved water. All dielectric strength tests were taken with a 0.20-inch gap setting

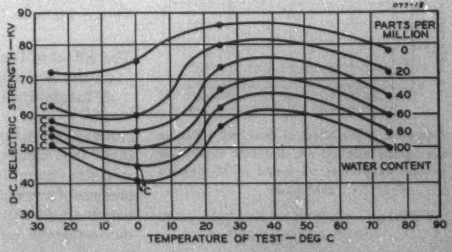



**Figure 18. The rapidly applied direct-voltage dielectric strength of transformer Pyranol as affected by temperature and its content of dissolved and suspended water**

Points marked C indicate that the oil contains suspended as well as dissolved water. All dielectric strength tests were taken with a 0.20-inch gap setting

normally refined transformer oil is about 70 parts per million. The higher water contents of figure 11 are, therefore, cloudy suspensions. It is only with wet oil free from suspended water that a clear effect of dissolved water on the dielectric strength can be demonstrated. The dielectric strength for oil containing suspended water is independent of the water content within the limits explored (figure 13). For tests at lower temperatures similar results are obtained.

Synthetic, noninflammable transformer liquids of the Pyranol type have already been described as possessing a maximum dielectric strength at about 50 degrees centigrade.[19] As illustrated in figure 14 this is true for such liquids only when containing small amounts of dissolved moisture. With increased water content the dielectric strength rises continuously with the increasing temperature of test.

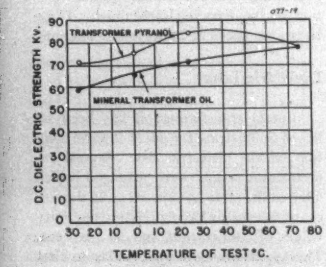



**Figure 19. The comparative dielectric strength of dry mineral transformer oil and dry transformer Pyranol tested under direct-voltage application**

All dielectric strength tests were taken with a 0.20-inch gap setting

Insulating liquids of the Pyranol type, as shown in figure 14, are characterized by a continually decreasing dielectric strength with increased water content. No abnormality in the relation is observed at the point of cloud formation, indicative of water separation from solution.

The Pyranol type of transformer insulating liquid in normally dry condition possesses a dielectric strength which is superior to that of mineral transformer oil. Figure 15 compares the dielectric strength of these two typical transformer liquids as affected by temperature when dry. Figure 16 compares the dielectric strengths of the two liquids each containing 40 parts per million of dissolved water.

## The Effect of Dissolved Water on the D-C Dielectric Strength of Insulating Liquids

Under rapidly applied direct voltage, transformer insulating liquids behave in a manner similar to that already described for a-c breakdown. Figure 17 describes the d-c breakdown of mineral transformer oil as a function of temperature and water content. The general resemblance to the a-c breakdown values of figure 11 is marked. The effect of dissolved water is most clearly demonstrated in the 75-degree-centigrade tests. And again, as in the alternating-voltage breakdown, the formation of a cloud in the oil tends to obscure the effect of further water additions.

Figure 18 describes the d-c dielectric-strength characteristics of transformer Pyranol. As in the a-c breakdown data of figure 14, the effect of water content on the dielectric strength is marked.

Figures 19 and 20 compare the d-c breakdown characteristics of mineral transformer oil and transformer Pyranol. Figure 19 compares the materials in the dry condition. Figure 20 compares the materials each containing 40 parts per million of water. The dielectric strength of transformer Pyranol is generally higher than the dielectric strength of mineral transformer oil except at 75 degrees centigrade, at which temperature the two liquids appear of equivalent dielectric strength under direct-voltage tests.

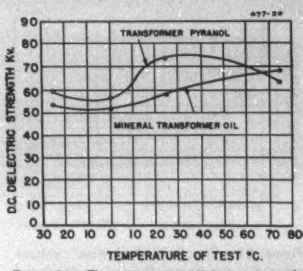



**Figure 20. The comparative dielectric strength of mineral transformer oil and transformer Pyranol each containing 40 parts per million of dissolved and suspended water and each tested under rapidly applied direct-voltage application**

All dielectric strength tests were taken with a 0.20-inch gap setting

## The Time-Voltage Relation

The time-voltage characteristic applying to an insulating liquid is a property of difficult determination because of the sharp "knee" which is obtained in the relation at a relatively short time interval. That part of the time-voltage relation which parallels the time axis and which designates the voltage that can be

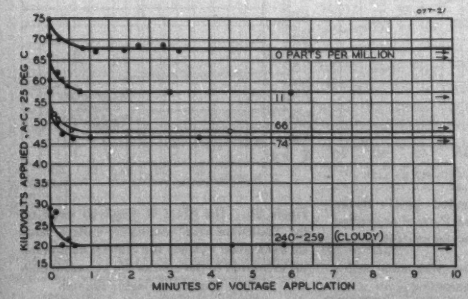



**Figure 21. The time-alternating (effective) voltage relation for transformer Pyranol as affected by the dissolved and suspended water content**

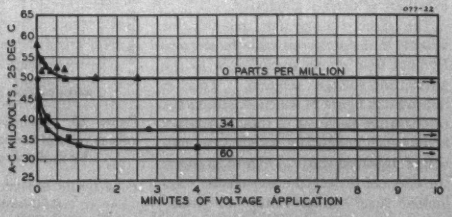



**Figure 22. The time-alternating (effective) voltage relation for mineral transformer oil as affected by the dissolved water content**

An arrow indicates that repeated applications of the voltage shown gave no dielectric breakdown within the time limitations of the test. All dielectric-strength tests were taken with a 0.20-inch gap setting

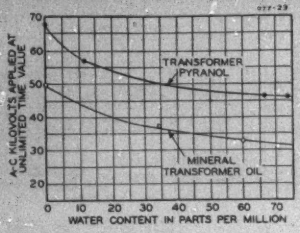



**Figure 23. The "unlimited time" voltage value for transformer Pyranol and mineral transformer oil as affected by the water content of the liquid**

All dielectric-strength tests were taken with a 0.20-inch gap setting

former Pyranol over the range of water contents of practical interest.

## The Relation of the Rapidly Applied to the "Unlimited Time" Breakdown Voltage

In the use of insulating liquids it is most convenient and reliable to gauge the dielectric strength by means of a carefully controlled rapidly applied alternating-voltage test. The determination of the "unlimited time" voltage is difficult and time consuming. For both transformer Pyranol and mineral transformer oil, the "unlimited time" voltage falls to approximately 70 per cent of the usual rapidly applied dielectric strength value as the

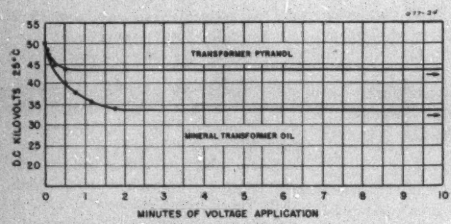



**Figure 24. The time – direct-voltage relation for transformer Pyranol and mineral transformer oil each containing 60 parts per million of dissolved water**

An arrow indicates that repeated applications of the voltage shown gave no dielectric breakdown within the time limitations of the test. All dielectric-strength tests were taken with a 0.20-inch gap setting

applied without fear of breakdown within the experimental time limit, is called the "unlimited time" value of voltage. In general, the maximum time allowed for breakdown in the work described has been limited to ten minutes. The electrodes used were duplicates of those employed in the rapidly applied test investigations and were spaced 0.20 inch apart. All tests were at 25 degrees centigrade. Both direct and alternating (effective) voltages have been studied.

Figures 21 and 22 describe the time-voltage (a-c) relation for transformer Pyranol and mineral transformer oil as affected by the dissolved and suspended water content. Figure 23 compares the effect of dissolved water on the "unlimited time" voltage values for mineral oil and Pyranol. The relations established are of marked similarity.

The direct-voltage–time relation for mineral transformer oil and transformer Pyranol bear strong resemblance to the alternating-voltage relation. This is indicated in figure 24 which illustrates the comparative behavior of these insulating liquids each containing 60 parts per million of dissolved water. Figure 25 shows the effect of dissolved water on the "unlimited time" direct voltage for transwater content of the liquid is increased at 25 degrees centigrade. The relation is illustrated in figure 26.

## The D-C/A-C Ratio of Dielectric Strength

The relation between the rapidly applied d-c and the a-c (effective) dielectric strengths of mineral transformer oil and

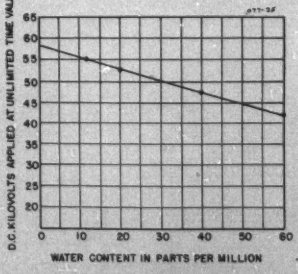



**Figure 25. The "unlimited time" direct-voltage value of transformer Pyranol as affected by its dissolved water content**

All dielectric strength tests were taken with a 0.20-inch gap setting

of transformer Pyranol has no fixed value. The ratio obtained for mineral transformer oil varies erratically between 0.89 and 1.58 as the temperature of test and the water content of the oil are changed. For transformer Pyranol, the range in d-c/a-c ratio value is between 0.89 and 1.37.

When the "unlimited time" voltage breakdown value is studied, a more consistent behavior of the d-c/a-c relation is observed. Figure 27 illustrates the ratio for transformer Pyranol using the "unlimited time" direct and alternating (effective) voltage values illustrated in figures 23 and 25. A ratio value linearly decreasing with the increased water content of the Pyranol is obtained. These tests were taken at 25 degrees centigrade.

## Dielectric Loss

Mineral transformer oil has been selected to illustrate the effect of water solution on the dielectric loss. Several experimental setups were arranged which allowed the oil to be exposed at 25 degrees centigrade to air having relative humidity values of 24 per cent and 65 per cent. The apparatus used was similar to that already described under the paragraph entitled "The Hygroscopicity of Dielectric Liquids." Power factor and resistivity measurements were made at 25 degrees centigrade. The power-factor measurement was at 60 cycles under 3,000 volts. The resistivity was measured after the application of 500 volts direct current for one minute. The electrode gap setting in all cases was 0.10 inch.

Figure 28 illustrates the power-factor results obtained. From the dry-oil condition the power factor rises rapidly with increased water content to reach a maximum stable value at about 15 parts per million of dissolved water. Figure 29

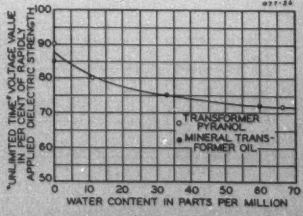

077-26
"UNLIMITED TIME" VOLTAGE VALUE IN PER CENT OF RAPIDLY APPLIED DIELECTRIC STRENGTH
TRANSFORMER PYRANOL
MINERAL TRANSFORMER OIL
WATER CONTENT IN PARTS PER MILLION

**Figure 26. The effect of dissolved water on the "unlimited time" alternating-voltage value for transformer Pyranol and mineral transformer oil expressed in per cent of the corresponding rapidly applied dielectric strength**

indicates a similar behavior for d-c resistivity measurements.

In considering the data of figures 28 and 29 it must be kept in mind that the oil tested was new oil uncontaminated by foreign materials or by oxidation products, the effect of which would necessarily be determined by their chemical and physical properties.

Cellulosic insulation is usually considered to be very susceptible to dielectric change caused by water. The presence of conducting salts and hygroscopic organic material serves to explain this marked susceptibility. Figure 30 describes the 30-degree-centigrade 60-cycle power-factor change in kraft-paper pads immersed in new mineral transformer oil and in new transformer Pyranol which are each exposed to humid air under conditions similar to those applying in the experimental setup of figures 28 and 29. The kraft-paper pads were originally well dried under a pressure about 0.3 millimeter of mercury at 100 degrees centigrade after which they were impregnated with the dry liquid. Although the data of figure 31 give no indication of the amount of moisture absorbed by the insulation, the test period covered several weeks and was sufficiently long for the insulation to reach an equilibrium with the water content of the surrounding liquid. Figure 30 leads to the conclusion that liquid-dissolved water does constitute a hazard to the successful maintenance of low-loss impregnated cellulose insulation. With new and unused insulating liquids, the 25-degree centigrade 60-cycle power factor of the impregnated cellulose insulation rises rapidly as the dissolved-water content of the impregnating liquid approaches and exceeds approximately 50 parts of dissolved water per million.

The effect on the power factor of liquid-immersed cellulosic insulation produced by moisture absorption becomes more pronounced as the temperature is raised above 50 degrees centigrade. This is illustrated in the data of figure 31. In this instance, carefully dried and impregnated kraft-paper insulating pads were immersed for 21 days at 70 degrees centigrade in transformer Pyranol, over the surface of which was maintained a layer of water about one-half inch deep. The sorption of water by the treated cellulose greatly increases the power factor at the higher testing temperatures.

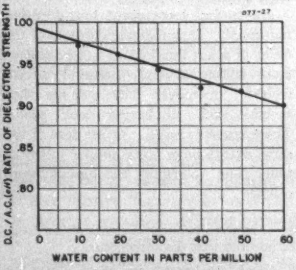



**Figure 27. The 25-degree-centigrade "unlimited time" d-c/a-c (effective) voltage ratio of dielectric strength for transformer Pyranol as affected by its dissolved water content**

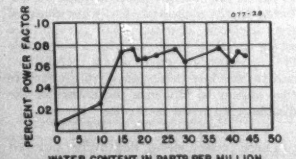



**Figure 28. The effect of dissolved moisture on the 60-cycle power factor of mineral transformer oil measured at 25 degrees centigrade**

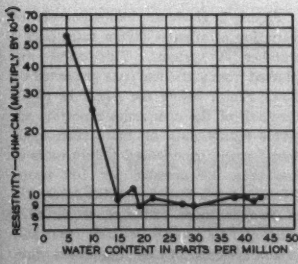
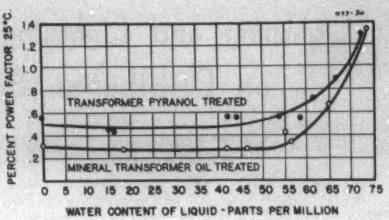



**Figure 29. The effect of dissolved moisture on the d-c resistivity of mineral transformer oil measured at 25 degrees centigrade**

**Figure 30. The power-factor characteristics of vacuum-dried kraft paper insulation as affected by water absorption after impregnation with transformer Pyranol and with mineral transformer oil**



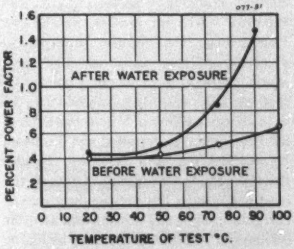




**Figure 31. The effect of water absorption on the power factor temperature relation for transformer-Pyranol-impregnated kraft-paper insulation**

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## Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

# Lightning and Lightning Protection on Distribution Systems

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THE CONCEPTIONS of lightning and of lightning discharge currents through arresters have been altered and enlarged by recent studies. Until not long ago the most complete information available on the magnitude and wave shape of lightning surges on electric systems has been that obtained by the cathode-ray oscillograph investigations of lightning voltages, reported and discussed before the AIEE,[1] and elsewhere. Besides this there exists a large mass of data on the crest magnitudes but not the durations of currents in lightning strokes and arrester discharges. Based on the data available two conclusions have been generally held: one, that in a small percentage of discharges, the currents may be high, perhaps 65,000 amperes or more; and two, that the total duration of the discharge might be of the order of 100 microseconds, but not much more. Lightning-arrester design was based principally upon these conclusions. Arresters available during the past six or eight years have in general been able to discharge high currents of the durations cited without damage. In the field, the over-all experience with such arresters has been good. Throughout the country the average failure rate of Autovalve distribution arresters manufactured during that period has been less than a quarter of one per cent per year. However, in rural locations in some parts of the country failure rates of three to four per cent have occurred. This is considered excessive. The variation in failure rates led to the suspicion, several years ago, that there are characteristics in arrester discharge currents that had not been taken into account and which are themselves influenced by such factors as lightning exposure, stroke characteristics, ground resistance, and system characteristics. It is true that to some extent the significance of the data may be obscured by failures from abnormal system voltages and by the performance of obsolete arresters, but these factors were not sufficiently weighty to explain the observations.

The purpose of this paper is to discuss the present state of our knowledge of this matter resulting from the observations and investigations of the authors and their colleagues. We do not propose to provide a complete answer at this time to the questions raised because insufficient field data exist. The authors hope that this paper will stimulate others to give the subject study. It is expected that a considerable volume of informative data will be available after another season's research with "fulchronographs," the recently developed surge wave recorders.

## Inspection of Arresters

A systematic inspection of Autovalve arresters removed from service was undertaken several years ago by our associates. Arresters that had failed in service as well as arresters which had not were examined. A surge discharge of high crest or of appreciable duration leaves a distinctive mark on the series-gap electrodes. This serves as an indication of crest current and duration if not obscured by power current. Crest currents above 3,000 amperes of short duration (less than 100 microseconds) leave marks like splashes. A low current of a few hundred to a thousand amperes of long duration (1,000 or more microseconds) produces a small pit with definite evidence of burning. Currents of high amplitude and long duration cause local melting of metal. A calibration of the appearance of the surge tracks as related to current magnitude and duration has been made. Typical results are shown in figure 1*a*.

Comparisons of electrodes from arresters that had seen service were made with the laboratory calibrations. Figure 1*b* shows representative field electrodes. These are especially significant because all but number 5 came from arresters installed on a line struck by lightning while it was unenergized. There is thus no question of masking by power current even in the cases where the arresters failed. Typical currents of high crest and short duration appear in 1, 2, and 3. The crests are of the order of 50,000 amperes and the durations approximately 50 microseconds. Number 2 has additional marks indicating other surges of lower crests. The elements of these arresters were not injured. Records 4 and 5 are typical low-current long-duration markings. They indicate currents of the order of a few hundred to 1,000 amperes crest lasting several thousand microseconds; moreover they indicate that several such discharges took place. These arresters failed. Other data of the same nature have given similar information. The following conclusions were reached:

1. Arrester discharge currents of low magnitude and long duration occur.
2. Such discharges are more likely to cause arrester failure than very high currents of short duration.
3. As far as arresters in service are concerned, either type of discharge may occur independent of the other.
4. It is important that field data be collected on the magnitude and wave shape of the discharge currents that prevail and which arresters must meet for a reasonable life expectancy under severe conditions; and to correlate these data with the factors that appear to influence the nature of the discharge currents in service.

These conclusions definitely pointed to a revision of our thinking about lightning-arrester discharge currents. Other observed circumstances strengthen this opinion.

## Statistical Data on Arrester Performance

Figure 2 gives an indication of the variation of arrester failure rates over a number of systems. This curve was plotted from statistical data presented by L. G. Smith before the AIEE in 1937.[2] One-half of the companies reporting arrester failure data on more than 1,000 transformers experienced failure rates of less than 0.3 arrester per 100 transformers, but a few reported failure rates of two or more. The paper shows a ratio of four to one between rural and urban systems. Other significant data were presented by McEachron and McMorris in 1938.[3] Many crest measurements without duration of arrester dis-

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The authors gratefully acknowledge the encouragement, guidance, and suggestions of L. R. Ludwig through these studies, as well as the important contributions made by A. M. Opsahl, W. G. Roman, F. B. Johnson, and W. B. Berkey; the aid given by C. F. Wagner and G. D. McCann in regard to field lightning; and the patient collection of a mass of laboratory data by J. L. Clark and C. M. Lear.

1. For all numbered references, see list at end of paper.

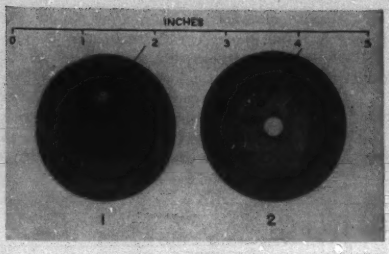



**Figure 1a. Surge marks on lightning-arrester gap electrodes obtained in laboratory tests**

1—57,000 amperes crest; 12 microseconds to crest; 26 microseconds total duration

2—725 amperes crest; 10 microseconds to crest; more than 4,000 microseconds total duration

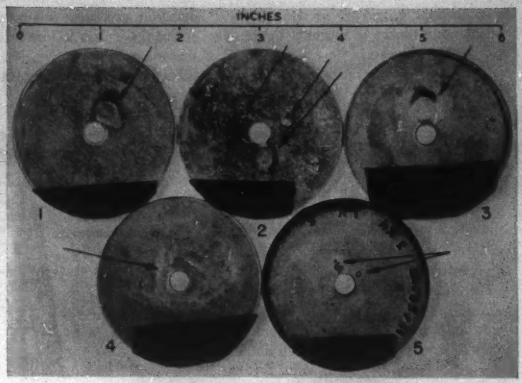



**Figure 1b. Surge marks left by lightning discharges through arresters in the field**

1—High short current

2—Several discharges of high short currents

3—High short current

4—Several discharges of moderate current. Several hundred amperes, but of long duration, probably more than 4,000 microseconds

5—Several discharges of moderate long current; 500 and 1,000 amperes, several thousand microseconds

All plates but number 5 from arresters on unenergized line

Arresters of 1, 2, and 3 were electrically undamaged. Arresters of 4 and 5 failed

charge currents are reported there and the occurrence of arrester failures is apparently not related to their magnitudes or to their relative frequency of occurrence on different systems in different parts of the country. Figure 7 of that paper is of considerable interest. It compares the frequency of occurrence of crest currents of various magnitudes on two different systems. Although the Detroit data indicate a greater prevalence of high currents, the observed failures of arresters are higher in Georgia. Low currents occur more often in Georgia than in Detroit. McEachron and McMorris report that 68 per cent of the observed arrester failures took place in Georgia although only 34 per cent of all the records were obtained there.

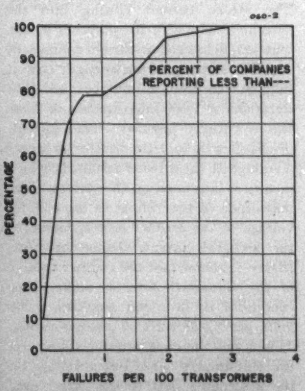



**Figure 2. Statistical data on the relation between number of companies reporting arrester failure rates on more than 1,000 transformers**

Number of companies considered, 33

Data culled from reference 2. Includes all protective circuits, average of 1934, 1935, and 1936 reported data

## Stroke Characteristics

Photographic studies of strokes by several investigators, for instance Schonland and Collens, and Walter, indicated the probability that strokes may not only be multiple but also may involve moderate or low-current components of considerable duration. Stekolnikov and Valeev[4] in 1936 made records of lightning currents to a captive balloon. A rotating klydonograph used by them indicated that the duration of current flow lay between 2,600 and 10,000 microseconds. McEachron's work on the Empire State Building[5] also gave evidence of this phenomenon. Last summer, Wagner and Beck[6] obtained a complete record of the current in a direct stroke to the Cathedral of Learning of the University of Pittsburgh which definitely showed both high short and low long components. The oscillograph studies on lines had not indicated that this occurred on systems, but the authors suspect that because of the sensitivity limitations of the cathode-ray oscillograph the low long component may have been present but not revealed.

There is definite evidence that the long low components will frequently, if not always, appear in strokes to tall conductors. It is probable that the characteristics of strokes to lines are different from those to high objects but there is sufficient evidence to be convincing that long-duration components appear also to some extent on lines when struck by lightning.

## New Recording Instrument

The available measurements of stroke currents cannot be translated into arrester duty until a significant volume of wave-shape data on strokes and arrester discharges in the field has been collected. This had not been done for lack of a recording device sufficiently low in cost to be installed in considerable numbers. The invention of the fulchronograph by Wagner and McCann described by them in a contemporary paper has made the needed device available.

It is evident that crest currents only without the important factor of duration did not give a complete understanding of arrester duty. The work has been begun. In co-operation with a number of utilities, many fulchronographs were installed during the summer of 1939, and already a considerable number of records has been obtained.

The fulchronograms of discharges through arresters in service are not yet of the desired technical significance. No records have been obtained accompanied by arrester failure. Records falling toward the expected extremes of high current or of long duration have not been secured. They do indicate, however, that arresters sometimes are called

upon to handle, and do so successfully, considerable blocks of current (figure 3) appreciably in excess of the existing AIEE standard test. The paucity of heavy surges is not unexpected, inasmuch as experience with fixed link records as well as with arresters indicates that harmless currents are much more frequent. Some typical fulchronograms are shown in figure 3. These are all records of discharge through individual phase legs of arresters. Numerous records have been made of discharges of less than 1,000 amperes and short duration.

The observations and tests discussed in the foregoing show that the occurrence of long-tailed moderate-current surges accounts for the abnormally high failure rates experienced in certain rural regions on the basis that in these regions arresters must discharge such surges more frequently. The ability of the De-ion protector such as is used in the *CSP* transformer, to handle currents of long duration probably accounts to a large extent for its low failure rate in service.

## Effect of System Characteristics

Low-current discharges through arresters are fairly common. This is demonstrated, for instance, by published data.[3] Figure 3 of the reference indicates that among 100 rural arrester installations, discharges of the following crest magnitudes (no data on duration) may be expected.

| Amperes exceeding: | 500 | 1,000 | 2,000 | 5,000 | 10,000 | 15,000 |
|---|---|---|---|---|---|---|
| Discharges per year: | 40 | 33 | 20 | 7 | 3 | 2 |

If the comparatively numerous low-current discharges through arresters were all or to a major extent of the long duration which might be expected from the observed stroke characteristics, laboratory tests on all types of distribution arresters would lead us to expect much higher arrester failure rates than those experienced and published.[3] Since many strokes evidently have these long low-current components there must be drainage effects present in many instances that relieve arresters installed on systems of some of this current.

Line flashovers from steep-front strokes to the line at points remote from arresters will by-pass a large proportion of the surge current. The effects of soil resistivity both on the degree of current drainage and perhaps on the character of the stroke itself may partly explain the difference in failure rates. In general, it has been found that where soil resistivity is high, arrester failures are more frequent. In addition to this, however, variations in arrester failure rates between locations resembling each other in insulation levels and soil resistivity point to another factor.

On grounded-neutral systems, both substation and distribution transformers are in parallel with the arresters and provide possible paths to ground for part of the current in long surges. A study was made of the current drainage characteristics of these shunt paths. The following discussion covers a typical example to illustrate the effects of system characteris-

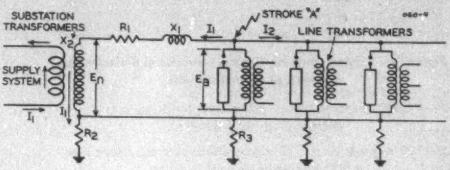



**Figure 4. Surge-current drainage paths in parallel with distribution arresters**

For $I_1$ see figure 5, and $I_2$ see figure 6

$E_a$—Arrester counter voltage

$E_n$—Alternating voltage to neutral

To use figure 5, calculate a-c short-circuit current at arrester nearest stroke with sufficient accuracy by using $R=(R_1+R_3)$ and $X=(X_1+X_2)$ (60 cycles), where $X_1$ is taken as 0.75 ohm per mile and $X_2$ is the substation transformer plus supply-system leakage reactance. Variation of $R_3$ through a 10–50 ohm range does not change $I_1$ appreciably

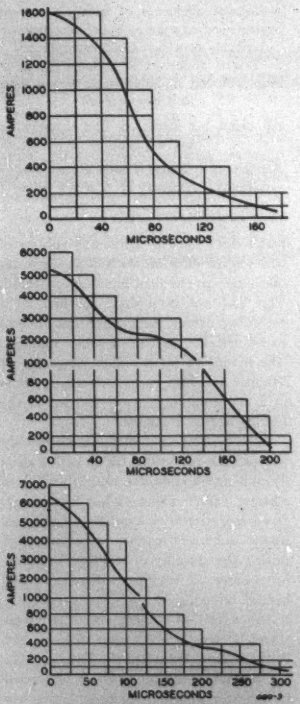



**Figure 3. Typical records of discharge currents through single-phase legs of lightning arresters in service, obtained with the fulchronograph**

Figure 4 is shown a long single phase circuit with distribution transformers and arresters, fed by a substation transformer. A stroke to the first arrester will discharge initially through it and possibly also through adjacent arresters depending on the surge front. With a steep-front stroke close to, or a slow-front stroke remote from an arrester, line flashover will not occur and all of the stroke current is carried by the arrester or arresters discharging first. The stroke current flowing into the system is assumed, for purposes of calculation, to have a low-current component of 1,000 amperes of such length that it may be considered a direct current. For durations of 1,000 microseconds or more this is entirely justified. This current, discharging through the arrester, produces a voltage at the arrester terminals, which in turn is impressed on the system. The magnitude of the voltage is the counter voltage of the arrester corresponding to the discharge current. Laboratory tests (figure 11) show that the counter voltage of the Autovalve arrester under these conditions is, in round numbers, 6,000 volts per 3,000 volts of arrester rating. This is not the crest arrester voltage on the volt-ampere curve but a voltage on the descending part of the curve, near the so-called "cut-off". The initial voltage while carrying high current can be neglected because of its short duration. For purposes of calculation, then, it is assumed that 6,000 volts per 3,000 volts of arrester rating are applied continuously to the resistance and inductance of the

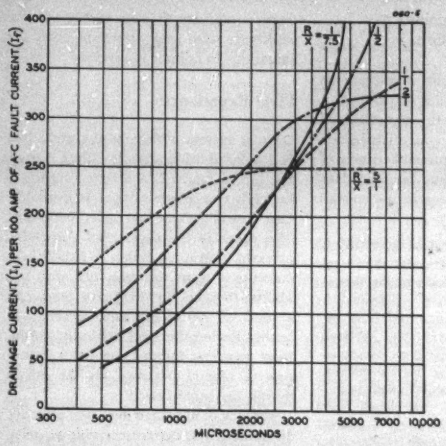



**Figure 5. Surge current drained from arrester through line conductors and substation transformers**

(Current $I_1$, in figure 4)

These curves based on $E_a = 2.5E_n$ which is an arrester counter voltage of 6,000 on a 2,400-volt circuit or 18,000 on a 7,200-volt circuit

Since the range of a-c fault current ($I_f$) on a feeder is generally known, the drainage current $I_1$, which is proportional to it, was plotted accordingly. To use the curves, calculate $I_f$ from $R$, $X$ (60 cycles) and $E_n$ of the figure 4 system, and use the appropriate $R/X$ ratio curve in plotting the leakage current $I_1$ versus time

circuits through the supply and distribution transformers. These were found to have entirely different characteristics.

The substation transformer has connected to its receiving winding the supply system of low impedance. The current $I_1$ of figure 4 to the substation ground will build up through the inductance of the line, the leakage inductance of the transformer and the supply source, that is, in the ordinary a-c short-circuit path. In figure 5, $I_1$ is plotted per 100 amperes of feeder fault current for several values of the ratio $R/X_{60}$. These curves apply to higher voltage as well as 2,400-volts-to-neutral systems because the arrester counter voltage is proportional to the arrester rating. With small conductors, ($R/X = 2/1$ to $5/1$, the drainage current to the substation ground is soon limited by line resistance.

The current $I_2$ flows in the other drainage path through the distribution transformers to ground. Since the secondary load impedances are high this current must build up through the magnetizing path. To determine the growth of current $I_2$, a $1^1/_2$-kva distribution transformer was subjected to suddenly applied continuous potential and the current measured by an oscillograph. Figure 6 shows the increase of current in terms of full load rms current of the transformers with 6,000 volts continuous applied to 2,400-volt windings or 18,000 volts applied to 7,200-volt windings. Until the iron begins to saturate at about 1,000 microseconds the current flow is imperceptible but after this it increases rapidly. The 1,000 microseconds applies under the conditions of test with no flux in the iron at the instant of application of the voltage. If the lightning voltage is applied at the instant the flux is zero, the curve applies as it stands. If the voltage appears when the flux is at its peak in the same direction, the time is much less, possibly zero. If it appears when the flux is at its opposite peak, the time will be much greater up to about twice 1,000 microseconds. To consider the most severe conditions it is assumed that 2,000 microseconds elapse before $I_2$ starts to flow.

The total current, $I_1$ plus $I_2$, that is drained away from arresters on typical 2,400- and 7,200-volt distribution systems is shown in figure 7. Up to 2,000 microseconds the drainage may be through the substation transformers only. Curves 1 and 2 show that for strokes near substations (3,000 to 1,000 kva, three phase) current is drained away rapidly. This also applies to a less extent on short heavy city feeders as shown in curve 3. Suburban and heavy rural circuits are represented in curves 4 and 5. Curve 6 applies to a typical rural circuit, while curve 7 represents extremely light rural distribution.

From curves 1, 2, and 3 of figure 7, it is apparent that for 1,000-ampere surges of long duration, the arrester discharge current will be reduced to zero in from 130 to 700 microseconds in city locations but for typical suburban distribution as indicated by curve 5, the arrester current will persist for some 2,500 microseconds where it is abruptly limited by drainage of current through the line transformers. The shape of curve 5 shows also that the suburban arresters are subjected to a higher average current.

On light rural systems the situation is the most unfavorable. The small size of the supply transformer and the high resistance of the line prevent much drainage to the substation. Fifteen miles of number 8 copper has a resistance of 53 ohms, which would pass only 340 amperes at the 18,000-volt counter voltage of a 9,000-volt arrester usual on a 7,200 volt system. Furthermore, the light branch fuses on these circuits are blown easily. With blown fuses, only the limited capacity of the distribution transformers can be depended upon for drainage, so conditions on grounded-neutral rural lines may be even worse than shown by curve 7.

In this connection it is suggested that the drainage of appreciable amounts of surge current through transformers may explain the occasional blowing of light transformer fuses with arresters connected on the line side of the fuses and no discernible evidence of flashover on the transformers.

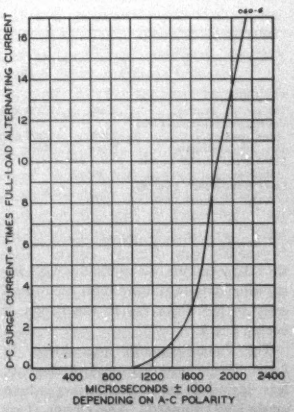



**Figure 6. Surge current drained from arrester through magnetizing path of line transformers**

(Current $I_2$ in figure 4)

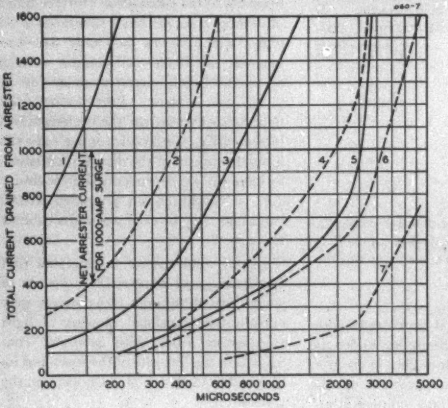
Based on applying direct voltage of 2.5 times rms alternating voltage rating of transformer, that is, $E_a = 2.5E_n$ (figure 4) which is an arrester counter voltage of 6,000 on a 2,400-volt circuit or 18,000 on a 7,200-volt circuit. Load impedance is so high that secondary was considered open-circuited

While there are other factors already enumerated to be considered, experience has shown that the failure rate of arresters increases progressively with conditions represented by the ascending curve numbers of figure 7. We would also expect from this analysis that arrester failure rates on free-neutral systems should be higher than on grounded-neutral systems. It is further significant that the locations of abnormally high distribution-arrester failure rates mentioned early in the paper fall in the region of curves 5 to 7.

The fulchronograms reproduced in figure 3 were recorded on arrester phase legs installed at a transformer whose neutral is grounded. The circuit characteristics are such that for the assumptions made in figure 7, the current drained from the arresters should be in the region of curve 2. This curve predicts an arrester discharge duration of not much more than 300 microseconds. The fulchronograms of figure 3 appear to corroborate the calculations. Apparently, all of the evidence available to date supports the conclusions.

## Application of Conclusions to Arrester Construction

The observations and investigations discussed in the foregoing explain to a large extent, at least, the variations in arrester failure rates on distribution systems as well as the probable causes of high failure rates. Thus far, the data presented are relative because not enough information on the actual wave shapes of discharge currents through arresters are at hand. Nevertheless, the conclusions appeared of sufficient importance two years ago to warrant an active investigation of arresters' ability to handle long discharges with the object of increasing this ability, without sacrifice of any of the high current capacity or protective characteristics. After all, the significance of the conclusions lies in whether they can be translated into a new and better arrester. Experience with an arrester tailored to these new concepts has been favorable. It gives additional corroboration and clarification to the aspects already discussed. The extremely low failure rate experienced with these arresters indicates that an increase in the ability to take long surges increases the immunity to failures in service.




Below 2,000 microseconds, all current flows to the substation. (Current $I_1$ calculated from figure 5). Above 2,000 microseconds, the line transformers begin to saturate and $I_2$, calculated from figure 6, increases sharply. Actually, this may occur at any time from zero to 2,000 microseconds, depending on the instantaneous magnitude and polarity of the a-c magnetic flux in the iron at the time of the stroke. Refer to table below

**Figure 7. Total current drained from arresters through transformers of typical distribution systems**

| | Curve Number: | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Voltage to neutral | 2,400 | 7,200 or 2,400 | 2,400 | 7,200 | 2,400 | 7,200 | 7,200 |
| Substation transformer kva per phase | 1,000 | 1,000 or None | 333 | 1,000 | 333 | 333 | 50 |
| Size line conductor | None | None | None | No. 00 | No. 4 | No. 2 | No. 4 | No. 8 |
| Miles from stroke to substation | 0 | 0 | 0 | 2 | 5 | 5 | 20 | 15 |
| Line transformer kva assumed all at one point | 0 | 0 | 0 | 0 | 300 | 200 | 100 | 75 |

## Field Experience

On a system which, in the past, has had a distribution-arrester failure rate at the top of figure 2, a direct comparison between two arrester types is available. One type is the new one under discussion. The other is the superseded Autovalve arrester, with equal ability to handle high currents of short duration, but with less ability to take the long low ones. In a total of 950 of the new arresters in service during the 1939 lightning season, there were no failures, against a failure rate of several per cent on the others during the same period.

For lack of measured data, the ultimate demands in long current-carrying capacity are not yet known. Nor is it known exactly what can be done economically to meet what those ultimate demands may turn out to be, or to what degree the new arrester meets them. It will not eliminate failures entirely. However, on the basis of laboratory tests and field experience, it is expected that even in the unfavorable locations the failure rate will be low.

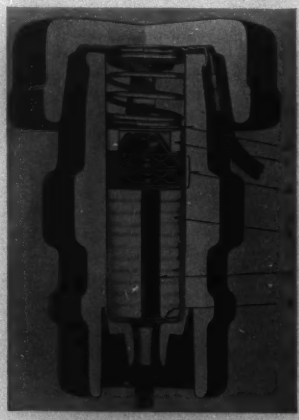


**Figure 8. 3,000-volt Autovalve distribution lightning arrester, cutaway section**

1—Porcelain-insulated main gap
2—Gap electrode with preionizing tips
3—Quenching gaps
4—Autovalve element with white insulating coating
5—Insulating coating cut away from element for purpose of illustration
6—Terminal plate, ground lead, and ferrule soldered together

The first field-trial installations were made in 1939, to gather operating experience before the design was adopted for production. Several thousand units were placed in locations where previous failure rates have been higher than normal. Two hundred fifty were in service throughout the 1938 season. No failures occurred. By the end of 1938 some 1,200 were installed. Before the spring of 1939, the number was 4,000, and this had more than doubled by the fall. There has been a total of four failures; one of these was definitely caused by system voltage. The other three occurred late last summer on the same system near the ends of lines. Inspection of these three arresters indicated that they were caused by lightning. Thus the lightning failure rate has been 0.043 per cent compared to the quarter of a per cent mentioned in the first paragraph of this paper.

## Construction

The principal factor in determining the ability of the arrester to discharge long surges is the valve element. Its failure can be thermal, or it can be caused by a function involving current density, voltage gradient, and duration of discharge. In long-duration discharges the latter cause is more weighty than the thermal. The recognition of this was important for it pointed out a means of making a distribution arrester of large current-carrying capacity without increasing its cross section. If the length of the block is doubled and its composition adjusted so that the total voltage across it during discharge is the same as in the case of the shorter element, the voltage gradient is halved. This reduction in voltage gradient effects a large increase in the ability of the elements to handle discharges of long duration. The use of such an element in the arrester is the major reason for its large discharge ability. Other detail features permit the utilization of the valve material to its full capabilities; such as a newly developed insulating coating and a particular design of terminal for making contact with the valve blocks.

The series gap structure consists of a quenching gap, item 3 in figure 8 with high 60-cycle interrupting ability, and a porcelain-insulated line or main gap, items 1 and 2. The high interrupting ability of the gap provides a margin of safety against failures from high system voltage. The use of mica spacers in the quenching gap and of a special main gap electrode, item 1, provides preionization of the gap spaces and produces low and consistent impulse breakdowns, as illustrated in oscillogram 1 of figure 9, which also shows the discharge characteristics of the arrester on the basis of AIEE standards. The favorable impulse ratios obtained with this construction permit the incorporation of a high 60-cycle breakdown, thereby providing additional margins against dynamic voltage failures.

During the development of this arrester, many tests were made with moderate discharge currents of long duration as well as with high currents. A novel test was completed when a lightning stroke occurred to a measuring station on the roof of Pittsburgh University's Cathedral of Learning.[6] The entire stroke current was discharged through one of the new distribution arresters, connected in the stroke-current circuit, and was recorded by a fulchronograph. This current is shown in figure 10. Subsequent laboratory tests on the arrester showed that its condition had not been altered by the discharge. As far as the authors are aware, this is the first time that an arrester has deliberately been put in the path of a stroke and successfully discharged the full stroke current. The performance of the arrester on laboratory surges of long duration and of high magnitude are shown in figures 11 and 12. Oscillogram 1 of figure 11 is typical in shape of the surge used in routine testing of valve elements to insure the use in complete arresters of only

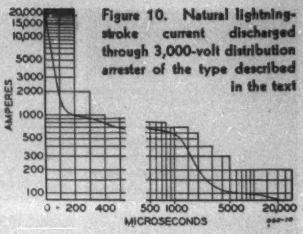
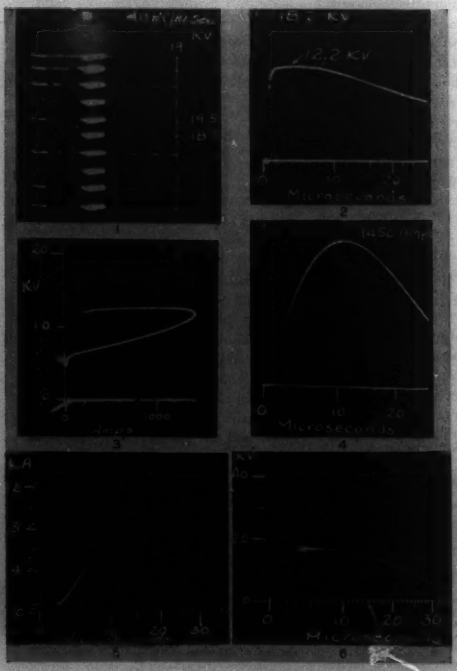



**Figure 10. Natural lightning-stroke current discharged through 3,000-volt distribution arrester of the type described in the text**

The current was derived from a lightning stroke to the Cathedral of Learning Building in Pittsburgh.[6] The current was recorded by a fulchronograph. After this test, the arrester was checked in the laboratory and found unchanged in its characteristics



1—Successive impulse breakdown tests on a 3,000-volt arrester. Rate of rise of test voltage 40 kv per microsecond. No time deflection used in oscillograph. Voltage deflection from left to right. Vertical line marked 19 is crest of 60-cycle breakdown

2—Volt-time curve of same arrester on AIEE test wave shown in 4

3—Volt - ampere characteristic of same arrester, test current as in 4

4—Ampere - time characteristic of test current used in 2 and 3

5—Ampere - time characteristic of 9,000-ampere test current used in 6

6—Volt-time characteristic of 3,000-volt arrester on test wave shown in 5

**Figure 9. Impulse characteristics of new distribution arrester**

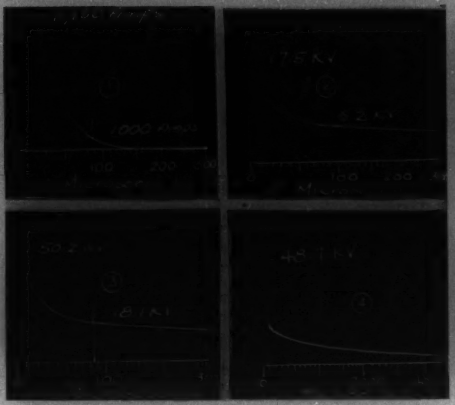


**Figure 11. Performance of distribution arrester on long surge**

1—Discharge current through arresters used in recording 2, 3, and 4

2—Volt-time characteristic of 3,000-volt arrester with discharge current of 1

3—Volt-time characteristic of 9,000-volt arrester with discharge current of 1

The points on 2 and 3 marked 6.2 and 18.1 kv are the voltages corresponding to 1,000 amperes in 1. These are the basis for assuming 6,000 volts per 3,000 volts of arrester rating in the derivation of figures 5, 6, and 7

4—Volt-time characteristic of 9,000-volt arrester with long time scale. This oscillogram shows that there is voltage across the arrester even after 4,000 microseconds, indicating that the arrester is still discharging current. In 1, the current is not discernible after 150 microseconds because of the current scale used

elements able to handle long-tailed discharges.

This test surge used on distribution arrester elements resembles the recorded discharge currents of figure 3, but is longer in duration. The routine test is made while the arresters are excited at rated 60-cycle voltage. The adoption of such a test procedure is perhaps as important a development as the new construction used in the arrester.

Other characteristics have been given due weight in the development, such as safeguards against lockouts by failed arrester on low-capacity systems, and the avoiding of interference with radio reception. Discussion of these is without the scope of this paper. However, the authors wish to say a few words on the matter of radio interference.

Radio interference has not been a problem in arresters constructed during the past eight years. Laboratory tests with standardized radio-noise-measuring technique are factors in the development of any arrester. However, a considerable amount of attention is being directed to this subject as well as to so-called ionization currents, synonymous with radio-noise currents. For this reason it is to be desired that the committees concerned with this question adopt standards of permissible microvolt levels to which the industry will subscribe and adhere. In this connection, it may be of interest that in the arrester discussed in this paper the occurrence of low ionization currents at a voltage below actual arrester breakdown but above its rating is promoted and utilized to achieve low and consistent impulse breakdown.

## Summary

The text of this paper concerns itself almost entirely with one aspect of the problem of distribution circuit protection, that of arrester discharge currents and the lightning-arrester failure rate. There are other phases of the problem such as the important one of protection to equipment. At this time, however, it is believed that the most important problem is the matter

**Table I. Summary of Arrester Characteristics**

| Arrester rating, volts. | 3,000 | 6,000 | 9,000 |
|---|---|---|---|
| 60-cycle breakdown, volts rms | 14,000 | 24,000 | 35,000 |
| Impulse breakdown, volts crest* | 20,000 | 40,000 | 58,000 |
| Discharge voltage at: | | | |
| 1,500 amperes† | 12,500 | 25,000 | 37,500 |
| 5,000 amperes† | 15,000 | 30,000 | 45,000 |
| 10,000 amperes† | 17,500 | 35,000 | 52,500 |
| 20,000 amperes† | 18,500 | 37,000 | 55,500 |

The above values are average.
* On front of 50 to 100-kv-per-microsecond test wave.
† 10 by 20-microsecond current wave.

**Figure 12. Performance of distribution arrester on high discharge currents**

1—High current discharge through 3,000-volt arrester

2—Volt-time characteristic of 3,000-volt arrester with discharge current of 1

3—High current discharged through 9,000-volt arrester

4—Volt-time characteristic of 9,000-volt arrester with discharge current of 3

The difference in current between the 3,000- and 9,000-volt arresters is caused by the difference in the counter voltage of the two. Both were tested in the same surge-generator circuit. The voltage across the 9,000-volt arrester for the current in 1 is three times the voltage recorded in 2

of eliminating as far as possible the failures of protective devices even under severe operating conditions. It is hoped that the work described in the paper has contributed to the solution of this problem, and there is some reassuring evidence that it has, contained for instance in the field records of an arrester designed to meet conditions disclosed by the studies already outlined.

Much research has been done on lightning, particularly on the lightning stroke. This will no doubt result, in time to come, in important new concepts of protection. However, the present practical aspect of the protective problem is concerned with the discharges through lightning protective devices in service, and not with the currents in direct strokes. For this reason, the authors attach the greatest importance to an accumulation without delay of a volume of statistical data on the magnitude and wave shape of such discharge currents, to permit a definite evaluation of the present means of protection, the economic possibilities,

# Watt-Hour-Meter Performance With Power Rectifiers

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**Synopsis:** This paper gives the results of tests made principally to determine the effect of 6- and 12-phase mercury-arc power-rectifier loads on the performance of typical polyphase watt-hour meters. Schematic diagrams of the connections used and oscillograms of the rectifier voltage and current waves are included. The results indicate that the effect to be expected will be well within one per cent.

IT IS well known that mercury-arc power rectifiers introduce harmonics in the alternating supply current and voltage waves [1-4] and this has been thought to affect adversely the accuracy of watt-hour meters on circuits including rectifiers. The subject has been investigated previously, notably by Dannatt,[5] but interest in it is still current. It was considered highly desirable, therefore, to make more comprehensive tests, utilizing the best obtainable equipment and methods, to determine the actual effect of commercial types of 6- and 12-phase rectifiers under approximate conditions of service on the performance of typical polyphase watt-hour meters used with instrument transformers. At the suggestion of W. C. Wagner, a var-hour meter (reactive-volt-ampere or rva-hour meter) was included; also included was a portable power-factor meter.

In these tests, the performance of five watt-hour meters was determined at various loads, first with one of the two rectifiers and second with a sine-wave supply under corresponding three-phase conditions. The differences between the meter accuracies thus obtained are a measure of the effect of the rectifier and are referred to the sine-wave results as a standard. A similar procedure was followed for the var-hour and power-factor meters.

The paper first summarizes the test results, then describes briefly the apparatus tested and the related theories of performance, outlines the procedure followed, and discusses the data obtained. The ratings of the apparatus are given in table I and part of it is shown in figures 1 and 2. Schematic diagrams of the test connections are shown in figures 3 and 4 and the measurement equipment in figure 5.

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The authors desire to acknowledge the assistance of G. F. Gardner and of many other of their associates in carrying out the tests.

1. For all numbered references, see list at end of paper.

## Summary of Results

The results of the watt-hour meter tests are given in table II, which shows that the maximum change in watt-hour meter performance due to the effect of the rectifiers is less than 0.5 per cent. Table II gives the detailed effects or the differences between the accuracies obtained with the rectifiers and with a sine-wave supply at corresponding points for the five watt-hour meters tested. The accuracies so obtained in the 6-phase rectifier tests are included in table III and are plotted in figure 8; the 12-phase rectifier results are plotted in figure 9. In general, the results obtained with the two rectifiers and the two types of meters are similar in magnitude. In both tests, the rectifier effect tends to decrease the meter speed at light load. At higher rectifier outputs, the 6-phase effect tends to increase the meter speed, whereas the 12-phase effect becomes negligible.

Three representative oscillograms taken during the 6-phase rectifier tests are shown in figure 6 and the analyses are given in table IV, part 1. This table includes an analysis of the oscillogram shown in figure 7 for a 12-phase rectifier. The maximum harmonics occur with the 6-phase rectifier, but the harmonic power is small, as indicated in table V.

The results of the var-hour meter tests are given in table III and are plotted in figure 10. The maximum change shown in var-hour meter performance due to the 6-phase rectifier is less than one per cent. The rectifier effect tends to increase the meter speed at light load and to decrease it at higher outputs.

Table III also gives the results of the power-factor meter tests, together with the instrument readings from the watt-hour meter tests. Three values of power

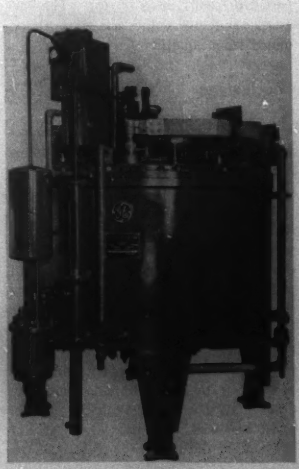

**Figure 1. Six-phase mercury-arc power-rectifier tank rated type RHW, 1,675 kw, 515 volts**

and the prediction of the failure rates of protective devices under the conditions of service that are encountered.

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## Discussion

Discussion will be found in the 1940 annual TRANSACTIONS volume and in the 1940 "Transactions Supplement" to ELECTRICAL ENGINEERING.

factor are given for each pair of tests as follows:

(*a*). Power-factor-meter reading

(*b*). Power factor calculated from the formula

$$\text{power factor} = \text{polyphase watts/voltamperes} = P/\sqrt{3}EI \quad (1)$$

(*c*). Vector power factor calculated from the formula

$$\text{vector power factor} = \text{polyphase watts} \div \sqrt{\text{watts}^2+\text{vars}^2} = P/\sqrt{P^2+Q^2} \quad (2)$$

Formulas 1 and 2 are based on American Standards Association definitions; they are here restricted to balanced circuits, as is (*a*).

With the sine-wave supply, the power-factor-meter readings (*a*) in table III agree fairly well with the two corresponding calculated values of power factor (*b*) and (*c*) in each case. With the 6-phase rectifier, the expected good agreement is shown between the power-factor-meter readings (*a*) and the corresponding calculated values of vector power factor (*c*). Good agreement is not expected between the power-factor-meter readings (*a*) and the corresponding calculated values of power factor (*b*) based upon the ASA definition; the maximum difference shown is 0.030 (=0.976–0.946) or about three per cent: this difference is a function of the harmonics present.

The rectifier effect represented by the difference between (*a*) and (*b*) may be expressed by the ratio (*a*)/(*b*), which here has a maximum value of 1.032 (=0.976/0.946), or as (*c*)/(*b*). The lowest power-factor values are those determined from equation 1.

## Conclusions

The rectifier current and voltage waves obtained in the tests are believed to be fairly representative of those encountered in practice.

The maximum effect of such rectifier waves on the performance of watt-hour meters should be well within one per cent; this conclusion is based upon all of our experience to date. The corresponding limit for a var-hour meter should be two per cent.

The effect of a 12-phase rectifier on the power factor should be less than the three per cent (ratio 1.032) obtained with the 6-phase rectifier. For both 6- and 12-phase rectifiers, the ratio (*a*)/(*b*) should aproximate the ratio

$$\frac{\text{effective value of balanced line currents}}{\text{effective value of fundamental component}} \quad (3)$$

when the harmonics in the balanced voltage waves are small as in these tests. The maximum value obtainable for ratio (3) with a 6-phase rectifier is 1.045 and it is 1.010 with a 12-phase rectifier. Thus, the maximum differences to be expected between the readings of a power-factor meter and the power factor calculated from equation 1 with such rectifiers should be within five per cent and two per cent, respectively.

The significance of the terms "power factor" and "reactive power" when harmonics exist in the system current and voltage waves is a matter of opinion[2–4].

The results upon which table II is based are believed to be correct within ±0.2 per cent.

A—Type DS-19

B—Type V-3-A

**Figure 2. Polyphase watt-hour meters rated 120 volts, 2.5 amperes, three-phase, three-wire, 60 cycles**

## Mercury-Arc Power Rectifiers

A 6-phase rectifier tank is shown in figure 1. The auxiliary equipment includes a main power-supply transformer in one or three units connected to convert 3-phase power to 6- or 12-phase power, an interphase transformer, vacuum pumps, and suitable control devices.[3,4]

The function of a complete rectifier is to convert a-c power to d-c power, usually for electric traction or electrochemical purposes. In so doing, it draws nonsinusoidal currents from a system generating sinusoidal voltages. These currents, in flowing through the system impedances, create nonsinusoidal voltage drops, which combine with the line voltages to give nonsinusoidal voltages at the rectifier terminals. The nonsinusoidal currents are composed of the fundamental and various harmonics, the orders of which depend on the number of rectifier phases; the magnitudes are an inverse function of the orders.[1] The nonsinusoidal voltage drops have the same harmonics, but the harmonic magnitudes depend on the magnitudes of the system impedances as well as on the magnitudes of the currents.[2] The formulas for the order and magnitude of the harmonic currents are as follows:

$$\text{Order of harmonic } n = mp' \pm 1 \quad (4)$$

$$\text{Per cent harmonic } h = 100/(mp' \pm 1) = 100/n \quad (5)$$

where

$m$ = any number from 1 to infinity

$p'$ = number of rectifier transformer secondary phases

The maximum obtainable percentage values of the harmonic currents due to the rectifier occur at light load and these estimated values are shown for 6- and 12-phase rectifiers in table IV, part 2*A*, up to the 25th harmonic, the fundamental being taken as 100 per cent; the orders of the harmonics also are shown. It should be noted that the magnitude of the harmonics decreases as their order increases and that harmonics common to both rectifiers, such as the 11th and 13th, have identical respective values. In practice, these magnitudes will ordinarily be somewhat less than those listed. Also, due to various causes, small amounts of the 5th, 7th, 17th, and 19th harmonics will be present with 12-phase rectifiers. For a given rectifier, the percentage harmonics will decrease with load, but the actual harmonic currents will increase; in other words, the harmonic components do not increase as fast as the fundamental.

Different rectifiers may be compared as to the relative amounts of harmonics expected in the input currents at full load by means of the load coefficient. The formula is:

$$\text{Rectifier load coefficient} = IX/E_a \quad (6)$$

Table I. Ratings of Apparatus Tested

| | Units | Type | Cycles | Phases | Kva | Kw | Volts | Amp |
|---|---|---|---|---|---|---|---|---|
| **Mercury-arc power rectifiers** | | | | | | | | |
| 6-phase rectifier | 1 | *RHW* | 60 | 6 | 1,675 | | 515 | 3,250 |
| | | | 60 | 6 | 2,233* | | 515 | 4,333* |
| Main transformer | 3 | *H* | 60 | 1 | 1,130 | | 13,200 | |
| Interphase transformer | 1 | *H* | 180/360 | | | | | |
| 12-phase rectifier | 1 | *RDW* | 60 | 12 | 2,000 | | 625 | 3,200 |
| Main transformer | 1 | *HTD* | 60 | 3 | 3,370 | | 14,200 | |
| Interphase transformer | 1 | *H* | 180/360 | | | | | |
| **Meters and instrument** | | | | | | | | |
| Two-element watt-hour meter | 3 | *DS*-19 | 60 | 3 | 0.52 | (*K* = 0.6) | 120 | 2.5 |
| Two-element var-hour meter | 2 | *V*-3-*A*, *BE*1 | 60 | 3 | 0.52 | (*K* = 0.6) | 120 | 2.5 |
| | 1 | *DS*-19 | 60 | 3 | 0.52 | (*K* = 0.6) | 120 | 2.5 |
| Double autotransformer | 1 | *MC*-1 | 60 | 3 | | | 115/115 | |
| Power-factor meter | 1 | *P*-3 | | 3 | 0.87 | | 100 | 5 |

* Extended rectifier rating.

where

$I$ = d-c load current per group of main-transformer secondary windings

$X$ = reactance of circuit in which commutation takes place

$E_0$ = crest voltage to neutral of main-transformer secondary winding

The effect of $IX/E_0$ at full load in reducing the light-load harmonic percentages is shown in table IV, part 2*B* for assumed values of 0.04 and 0.08: the latter is considered representative of many rectifiers. For example, take the 13th harmonic. For both rectifiers, "39" corresponds to 0.08, which means that 39 per cent of the light-load harmonic of 7.7 per cent will be present; this gives 3 per cent for the 13th harmonic: the corresponding value for $IX/E_0 = 0.04$ is 5 per cent. The percentage of harmonic present tends to decrease as the order of harmonic increases; the decrease for the 5th harmonic is small: conversely, the percentage increases with decreasing values of $IX/E_0$.

The term $X$ in $IX/E_0$ represents the sum of the system reactance and that of the rectifier transformer; the system reactance (and the losses therein) ordinarily is less than ten per cent of the total. The harmonic power to be measured, therefore, is but a small part of that due to the rectifier, which in turn is but a small part of the fundamental power. The harmonic and fundamental powers have opposite signs. If the system voltage itself contains some of the harmonics expected from the rectifier, however, the net harmonic power may be positive instead of negative.

Ratio (3) is a function of the harmonics in the input currents. The maximum value of 1.045 for this ratio with a 6-phase rectifier is obtained when all possible harmonics attain the maximum possible magnitude; table IV, part 2, includes those up to the 25th. The maximum value of 1.01 is similarly obtained with a 12-phase rectifier.

## Watt-Hour Meters

One of the type *DS*-19 watt-hour meters tested is shown in figure 2*A* and one of the type *V*-3-*A* meters in figure 2*B*. Both types have the same rating and are designed for three-phase three-wire service, usually with instrument transformers. The switchboard-type *DS*-19 meter employs two electromagnetic structures and two disks mounted on a common

**Figure 3. Schematic measurement circuits for rectifier tests**

*A*—Rectifier input and output
*B*—Rectifier supply for watt-hour meter tests
*C*—Rectifier supply for var (rva)-hour meter tests
*D*—Sine-wave supply for check tests

**Figure 4. Schematic instrument and auxiliary circuits**

*A*—Potential and current supply—load control for check tests
*B*—Meter-disk revolution counter

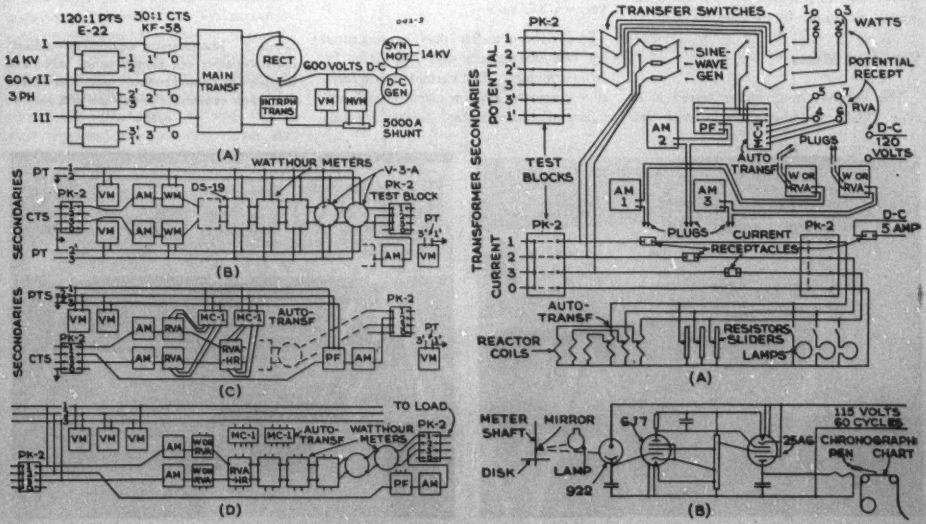

**Table II. Effect of Rectifiers on Watt-Hour-Meter Performance (Difference Between Rectifier and Sine-Wave Results)**

| Test Number | Rectifier Output (Per Cent) | Load Coefficient $IX/E_s$ | Input (P-3 Instruments) (Average of Three) Volts | Amp | Three-Phase Watts | Power Factor ($P/\sqrt{3}EI$) | Watt-Hour Meters; Per Cent Difference (Referred to Sine Wave) DS-19 1 | 2 | 3 | V-3-A 4 | 5 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **6-phase rectifier** | | | | | | | | | | | |
| 1 | 21.5 | 0.015 | 116.9 | 0.571 | 109.9 | 0.950 | −0.1 | −0.1 | 0 | −0.1 | −0.3 |
| 2 | 57.5 | 0.044 | 116.6 | 1.515 | 289.3 | 0.946 | −0.1 | −0.1 | −0.1 | −0.1 | −0.3 |
| 3 | 86.9 | 0.066 | 117.1 | 2.279 | 436.6 | 0.944 | +0.1 | +0.1 | +0.1 | +0.1 | −0.1 |
| 4 | 113.6 | 0.086 | 117.9 | 2.973 | 570.3 | 0.939 | | +0.1 | +0.2 | +0.1 | −0.1 |
| 5 | 135.8 | 0.105 | 118.3 | 3.568 | 684.6 | 0.936 | +0.2 | +0.2 | +0.2 | +0.1 | −0.1 |
| 6 | 154.2 | 0.120 | 118.1 | 4.078 | 777.8 | 0.933 | +0.1 | +0.2 | +0.2 | +0.1 | −0.1 |
| **12-phase rectifier** | | | | | | | | | | | |
| 1 | 18.2 | 0.008 | 118.2 | 0.551 | 108.4 | 0.961 | −0.2 | −0.3 | −0.4 | | −0.3 |
| 2 | 35.4 | 0.015 | 118.0 | 1.061 | 210.0 | 0.969 | +0.1 | +0.1 | +0.1 | +0.1 | +0.1 |
| 3 | 62.6 | 0.027 | 118.0 | 1.850 | 367.8 | 0.973 | 0 | 0 | 0 | 0 | 0 |
| 4 | 83.3 | 0.036 | 117.3 | 2.482 | 491.5 | 0.974 | 0 | 0 | −0.1 | 0 | 0 |
| 5 | 92.8 | 0.041 | 116.2 | 2.812 | 550.8 | 0.973 | 0 | 0 | −0.1 | 0 | −0.1 |

shaft. The bottom-connected type *V*-3-*A* meter employs a more recent construction, in which both electromagnets act on a common disk. Interference is rendered negligible by the use of magnetic shields and by laminating the disk, thereby segregating the fluxes and eddy currents.

Tests made here and elsewhere have shown that such induction-type meters tend to become slower as the applied frequency increases. Thus 60-cycle meters would be slow at 300 cycles; in other words, they would not register fifth harmonic power correctly and larger errors would be obtained with higher harmonic powers. In some cases, correlation has been shown[5,10,11] between the performance of a meter on distorted waves and its performance on the component harmonic frequencies.

## Var-Hour Meter

The var(rva)-hour meter tested is a type *DS*-19 watt-hour meter with its two potential circuits supplied from a type *MC*-1 double autotransformer instead of directly from the two line-to-line system voltages. By means of suitable taps, the autotransformer lags each voltage 90 degrees in order to measure the reactive component of the energy.[9] A similar unit supplied two indicating watt(var) meters to measure the reactive power.

The active power in a balanced three-phase three-wire sine-wave circuit may be determined from the formula

$$\text{watts} = \text{line-to-line volts} \times \text{line amperes} \times \sqrt{3} \times \cos\theta = \sqrt{3}EI \cos\theta \quad (7)$$

where $\theta$ is the angle between the voltage to neutral and the line current. Similarly, the reactive power may be obtained from the formula

$$\text{vars} = \sqrt{3}EI \sin\theta \quad (8)$$

The former quantity may be measured by two wattmeters and the latter by two varmeters. The varmeters will function correctly also on circuits with unbalanced currents, but neither formula can be used as the line currents are unequal and $\theta$ is meaningless. The wattmeters will function correctly on any sort of three-wire circuit.

Equations 7 and 8 may be used for balanced circuits and "$\theta$" may be taken to represent the "angle" between voltage and current when the current waves contain harmonics. However, each wattmeter then measures the product of its sine-wave voltage and the in-phase component of its current. Since the fundamental component is smaller than the total current, the correct power factor (by ASA definition) or cos "$\theta$" obtained from equation 1 will be smaller and "$\theta$" will be larger than if no harmonics were present. Therefore, sin "$\theta$" and the calculated reactive power will be larger than the measured value, the difference

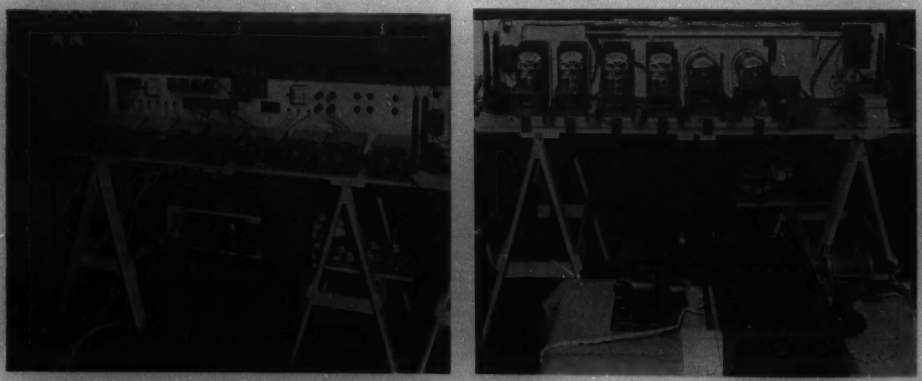

**Figure 5. Measurement equipment—indicating instruments and transfer panel, sine-wave loading devices and control—watt-hour meters, revolution counters, chronograph and oscillograph**

being a function of ratio (3). Also the vector power factor or cos $\theta$ determined from equation 2 will be the same as that read on a power-factor meter and both will be greater than the value determined from equation 1 in the ratio (3).

The foregoing discussion will still be pertinent when the harmonics in the voltage waves are small. However, it has been shown[3] that correct measurement of reactive power is impossible when the harmonics in both the voltage and current waves are appreciable.

## Power-Factor Meter

The type *P*-3 portable power-factor meter tested is designed for use on balanced three-phase three-wire circuits only and has one current coil, which is connected in series with the "common" line. There are two potential coils mounted at an angle on the shaft and the two potential circuits are connected from the other two lines to the "common" line. Essentially, two wattmeters are combined in one instrument without a control spring, so the deflection depends on the ratio of the two torques, which is a function of the power-factor angle $\theta$. The scale is marked in power factor and the range is from 0.5 lag through 1.0 to 0.5 lead.

## Test Connections and Procedure

The tests described herein were made in connection with the standard acceptance tests on the two rectifiers. The measurement equipment is shown in figure 5. The meter accuracies were determined first with one of the two rectifiers and second with the sine-wave supply. The correct three-phase watt (or var) values were obtained in each test from the readings of two single-phase watt (or var) meters, which were checked with the d-c supply by means of potentiometers. The correct power factor was calculated from equation 1, which requires the readings of eight different instruments.

### Connections

The connections used are shown schematically in figures 3 and 4. Figure 3*A* shows the general arrangement of the rectifier input and output circuits and indicates the feed-back scheme adopted for acceptance tests on large rectifiers. The small numbers on the instrument transformer secondary leads correspond to similar numbers in figure 3*B*, which shows the arrangement for the watt-hour meter tests. The arrangement for the

Table III. Watt-Hour, Var-Hour, and Power-Factor Meters (Six-Phase Rectifier and Sine-Wave Results)

| Test Number | P-3 Instruments (Average of Three) Volts | P-3 Instruments (Average of Three) Amperes | P-3 Instruments Three-Phase Volt-Amperes | P-3 Instruments Three-Phase Watts | P-3 Instruments Three-Phase Vars | (a) Power-Factor Meter | (b) Power-Factor $\left(\frac{P}{\sqrt{3}EI}\right)$ | (c) Vector Power-Factor $\left(\frac{P}{\sqrt{P^2+Q^2}}\right)$ | Reactive Factor $\left(\frac{Q}{\sqrt{3}EI}\right)$ | Watt-Hour Meters Per-Cent Accuracy DS-19 1 | DS-19 2 | DS-19 3 | V-3-A 4 | V-3-A 5 | Var-Hour Meter Per Cent Accuracy | Var-Hour Meter Per Cent Diff.* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Input to 6-phase rectifier (through instrument transformers)** | | | | | | | | | | | | | | | | |
| 1 | 116.9 | 0.571 | 115.7 | 109.9 | | | 0.950 | 0.958 | 0.238 | 100.1 | 99.9 | 100.1 | 100.0 | 99.8 | | |
| 1a | 117.0 | 0.592 | 119.9 | 28.52 | | 0.977 | | | | | | | | | 98.1 | +0.2 |
| 2 | 116.6 | 1.515 | 305.9 | 289.3 | | | 0.946 | 0.974 | 0.221 | 100.0 | 100.0 | 99.9 | 99.9 | 99.8 | | |
| 2a | 116.4 | 1.508 | 304.0 | 67.16 | | 0.976 | | | | | | | | | 99.4 | −0.1 |
| 3 | 117.1 | 2.279 | 462.3 | 436.6 | | | 0.944 | 0.972 | 0.232 | 100.1 | 100.1 | 100.1 | 100.1 | 99.9 | | |
| 3a | 117.0 | 2.266 | 459.4 | 106.5 | | 0.971 | | | | | | | | | 99.7 | −0.4 |
| 4 | 117.9 | 2.973 | 607.1 | 570.3 | | | 0.939 | 0.966 | 0.253 | 100.1 | 100.2 | 100.1 | 99.9 | | | |
| 4a | 117.8 | 2.956 | 603.2 | 152.4 | | 0.965 | | | | | | | | | 99.5 | −0.4 |
| 5 | 118.3 | 3.568 | 731.4 | 684.6 | | | 0.936 | 0.965 | 0.263 | 100.2 | 100.2 | 100.2 | 100.0 | 99.9 | | |
| 5a | 118.1 | 3.474 | 710.6 | 184.7 | | 0.962 | | | | | | | | | 99.3 | −0.6 |
| 6 | 118.1 | 4.078 | 833.9 | 777.8 | | | 0.933 | 0.958 | 0.277 | 100.1 | 100.1 | 100.2 | 99.9 | 99.8 | | |
| 6a | 119.3 | 4.063 | 843.6 | 233.4 | | 0.959 | | | | | | | | | 99.1 | −0.8 |
| **Supply from sine-wave alternator (direct)** | | | | | | | | | | | | | | | | |
| **Check Number** | | | | | | | | | | | | | | | | |
| 1 | 116.6 | 0.585 | 118.2 | 114.0 | | | 0.964 | 0.959 | 0.284 | 100.2 | 100.0 | 100.1 | 100.1 | 100.1 | | |
| 1a | 116.8 | 0.585 | 118.3 | 33.61 | | 0.972 | | | | | | | | | 97.9 | |
| 2 | 116.1 | 1.501 | 302.0 | 293.0 | | | 0.970 | 0.973 | 0.230 | 100.1 | 100.1 | 100.0 | 100.0 | 100.1 | | |
| 2a | 116.2 | 1.503 | 302.4 | 69.27 | | 0.975 | | | | | | | | | 99.5 | |
| 3 | 117.6 | 2.197 | 447.6 | 433.7 | | | 0.969 | 0.970 | 0.239 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | | |
| 3a | 119.0 | 2.215 | 456.5 | 108.9 | | 0.972 | | | | | | | | | 100.1 | |
| 4 | 118.4 | 2.942 | 603.3 | 579.7 | | | 0.961 | 0.964 | 0.265 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | | |
| 4a | 118.4 | 2.946 | 604.1 | 160.5 | | 0.963 | | | | | | | | | 99.9 | |
| 5 | 117.5 | 3.564 | 725.4 | 694.3 | | | 0.957 | 0.962 | 0.272 | 100.0 | 100.0 | 100.0 | 99.9 | 100.0 | | |
| 5a | 117.7 | 3.567 | 727.1 | 195.0 | | 0.968 | | | | | | | | | 99.9 | |
| 6 | 117.4 | 4.038 | 820.9 | 782.7 | | | 0.953 | 0.959 | 0.282 | 100.0 | 99.9 | 100.0 | 99.8 | 99.9 | | |
| 6a | 117.7 | 4.037 | 823.2 | 232.4 | | 0.959 | | | | | | | | | 99.9 | |

* Difference between rectifier and sine-wave results; this is the rectifier effect: the watt-hour-meter differences are in table II. Power-factor columns (*a*), (*b*), and (*c*) are explained in the text of the paper.

A—At 22 per cent output

B—At 114 per cent output

C—At 156 per cent output

**Figure 6. Oscillograms showing wave shapes of voltage and current, six-phase mercury-arc power rectifier rated type RHW, 1,675 kw, 515 volts**

Curve *A*—Secondary current in line 1

Curve *B*—Secondary current in line 2

Curve *C*—Secondary current in line 3

Curve *D*—Secondary voltage across lines 1–2

var-hour and power-factor meter tests is shown in figure 3*C*. In *B* and *C*, meters not under test are indicated by dotted lines. Figure 3*D* indicates the arrangement for the sine-wave supply, which constituted the standard test condition for all meters.

The necessary connection changes were made by means of single- and double-throw potential switches, type *PK*-2 potential and current test blocks, and potential and current receptacles and plugs. These are shown in figure 4*A*. In the rectifier tests, the magnitude of the currents through the various instruments and the six meters (not shown) was determined by the load on the rectifier. In the sine-wave checks, the corresponding currents and power factors were obtained by means of the variable non-inductive and inductive loads shown at the bottom of figure 4*A*. The line-to-line voltages were set at approximately the desired values by means of remote generator field control.

The method of automatically counting the revolutions of the six meter disks is shown in figure 4*B*. A small mirror is fixed on each meter shaft to reflect the light from a small lamp to photoelectric tube 922. This tube operates the coil of a suitable pen through a tube network. Each pen records each revolution of its meter on the moving chronograph chart, which also is marked by two pens (one at each side of the chart) energized every second from a standard clock.

### Procedure

For a test run on the watt-hour meters with the rectifier supply, the chronograph chart was started and allowed to record the meter revolutions for a period of eight minutes, during which the two indicating wattmeters were read every ten seconds, making a total of 48 readings each. Readings were taken every 30 seconds on each voltmeter and ammeter, giving a total of 16 readings per instrument. Thus one observer was required for each wattmeter, one for the three voltmeters, and one for the three ammeters, making a total of four.

Next a test run was taken on the var-hour and power-factor meters and the chronograph chart was permitted to record the meter revolutions for five minutes, during which a total of 30 readings were taken on each of the two var-meters and on the power-factor meter and ten readings were taken on each voltmeter and ammeter. An extra observer was required for the power-factor meter.

The watt- and var-hour meter tests just described were checked by corresponding tests with the sine-wave supply, the secondary voltage, current, and power-factor values due to the rectifier load in each case being duplicated as closely as possible. The actual running time for the four tests at each load was 20 minutes.

Finally, the indicating watt (or var) meter readings taken in the a-c tests were checked with the d-c supply. Reversed readings were taken at each point, using two deflection potentiometers, one for voltage and the other for current, as standards.

After completing the tests, the readings of each indicating instrument were av-

**Figure 7. Oscillogram showing wave shapes of voltage and current at 100 per cent output, 12-phase mercury-arc power rectifier rated type RDW, 3,000 kw, 625 volts**

Curve *A*—Secondary voltage across lines 1–2

Curve *B*—Secondary current in line 1

Table IV. Actual and Estimated Percentages of Harmonics in A-C Input Waves

| Test Number | Phases | Rectifier Output (Per Cent) | Rectifier Load Coefficient IX/E₂ | Input (Average of Three) Kv | Input (Average of Three) Amp | Per Cent Harmonic: Harmonic Order and Frequency in Cycles Per Second 1st 60 | 5th 300 | 7th 420 | 11th 660 | 13th 780 | 17th 1,020 | 19th 1,140 | 23d 1,380 | 25th 1,500 | Oscillogram Figure Number |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **(1) Harmonic Analysis of Oscillograms** | | | | | | | | | | | | | | | |
| **Secondary current** | | | | | | | | | | | | | | | |
| 1 | 6 | 22 | 0.015 | 14.00 | 17.15 | 100 | 16.2 | 9.9 | 6.8 | 6.4 | 3.9 | 2.3 | | | 6A |
| 4 | 6 | 114 | 0.086 | 14.12 | 89.20 | 100 | 17.7 | 8.8 | 5.1 | 3.9 | 1.8 | 0.6 | | | 6B |
| 6a | 6 | 156 | 0.120 | 14.29 | 122.5 | 100 | 16.7 | 8.2 | 4.2 | 2.7 | | 3.6 | | | 6C |
| **Secondary voltage** | | | | | | | | | | | | | | | |
| 1 | 6 | 22 | 0.015 | 14.00 | 17.15 | 100 | 1.5 | 2.2 | 0.8 | 1.3 | 2.3 | | | | 6A |
| 4 | 6 | 114 | 0.086 | 14.12 | 89.20 | 100 | 1.7 | 1.1 | 2.2 | 2.8 | 0.6 | | | | 6B |
| 6a | 6 | 156 | 0.120 | 14.29 | 122.5 | 100 | 2.9 | 3.6 | 2.3 | 1.8 | 2.1 | | | | 6C |
| **Secondary current** | | | | | | | | | | | | | | | |
| † | 12 | 100 | 0.058 | 14.00 | 126.0 | 100 | 1.4 | 0.5 | 5.0 | 3.8 | 0.4 | 0.1 | 0.9 | 0.7 | 7 |
| **Secondary voltage** | | | | | | | | | | | | | | | |
| † | 12 | 100 | 0.058 | 14.00 | 126.0 | 100 | 0.2 | 0.1 | 1.3 | 1.1 | 0.2 | 0.1 | 0.3 | 0.1 | 7 |

**(2) Estimated Percentages of Harmonics in Current Waves Due to Rectifier**

**(A) Light-load values (up to 25th harmonic)**

| | | | Maximum Obtainable Per Cent Harmonics** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6 | 0–20 | * | 100 | 20 | 14.3 | 9.1 | 7.7 | 5.9 | 5.3 | 4.4 | 4.0 |
| 12 | 0–20 | * | 100 | | | 9.1 | 7.7 | | | 4.4 | 4.0 |

**(B) Full-load values**

| | | | Per Cent of Light-Load Values | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6 | 100 | 0.04 | 100 | 94 | 88 | 74 | 65 | 48 | 38 | 25 | 24 |
| 6 | 100 | 0.08 | 100 | 88 | 77 | 52 | 39 | 24 | 22 | 21 | 20 |
| 12 | 100 | 0.04 | 100 | | | 74 | 65 | | | 25 | 24 |
| 12 | 100 | 0.08 | 100 | | | 52 | 39 | | | 21 | 20 |

* The load coefficient has a negligible effect on the magnitude of the harmonics at light load.

** Based on an inductive load; for a noninductive load, the fifth harmonic value is higher (= 22.6) but the other harmonic values are lower (or unchanged), so the maximum possible composite value is practically unchanged.

† Test made on 3,000-kw rectifier.

eraged and corrected for scale error. To obtain the three-phase volt-amperes, the three corrected voltmeter readings in each test were averaged, as were the three ammeter readings and these average values $E$ and $I$ were used in the formula.

$$\text{three-phase volt-amperes} = \sqrt{3}EI \qquad (9)$$

In each watt-hour meter test, the polyphase watts were obtained by adding the corrected readings of the two wattmeters and these indicated watts constituted the standard of reference in determining the meter accuracies. The recorded meter watts were determined from the total revolutions recorded on the chronograph chart and the corresponding elapsed time. The accuracy formula is

$$\text{per cent accuracy} = \frac{\text{recorded watts}}{\text{indicated watts}} \times 100 \qquad (10)$$

A similar procedure was followed for the var(rva)hour meter, the formula being

$$\text{per cent accuracy} = \frac{\text{recorded vars}}{\text{indicated vars}} \times 100 \qquad (11)$$

In these tests, however, the polyphase vars were obtained from the difference between the two varmeter readings. The reactive factor (sin "$\theta$") was determined from the formula

$$\text{reactive factor} = \text{polyphase vars}/\text{volt-amperes} = Q/\sqrt{3}EI \qquad (12)$$

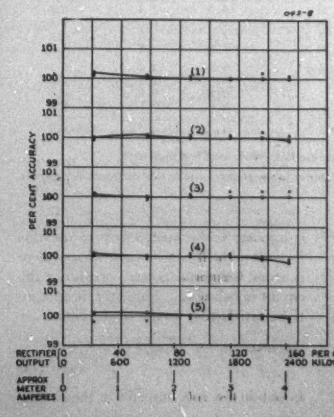


**Figure 8 (left). Watt-hour-meter accuracies with six-phase rectifier and with sine-wave supply**

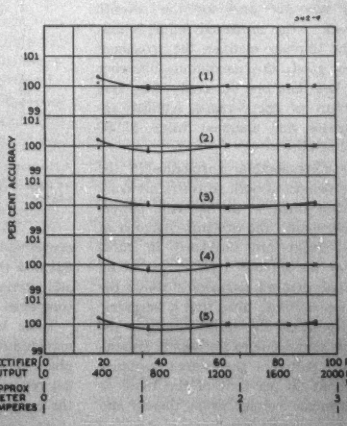


**Figure 9 (right). Watt-hour-meter accuracies with 12-phase rectifier and with sine-wave supply**

Curves 1, 2, 3—Type *DS*-19 meters

Curves 4, 5—Type *V*-3-*A* meters

Circles—Sine-wave supply

Crosses—With rectifier load

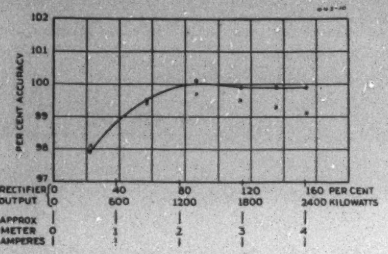


**Figure 10. Accuracy of type DS-19 var (rva)-hour meter with six-phase rectifier and with sine-wave supply**

Circles—Sine-wave supply
Crosses—Six-phase rectifier

Power factor ($\cos \theta$) was read directly on the power-factor-meter scale and for comparison was calculated from equation 2.

No corrections for the watts or vars were necessary because of the instrument transformers in the rectifier tests, since the meters were compared directly with the instruments in the secondary circuits.

## Discussion of Results

### Wave Shapes

A comparison of the current wave shapes in figure 6*A* at light load on the 6-phase rectifier with the theoretical waves, as shown by the magnitudes of the several harmonics in table IV, parts 1 and 2, indicates that the test harmonics are less than the theoretical ones by a maximum of about four per cent.

A much better agreement is found between the current wave shapes in figure 6*B* at rated output on the 6-phase rectifier and the theoretical waves based upon table IV, part 2*B*. The calculated harmonics check the test harmonics closely, the maximum difference being about two per cent for the seventh harmonic: the measured value is low. For the 12-phase rectifier, the agreement also is good, the maximum difference being less than one per cent. The load coefficient of the 6-phase rectifier approximates one assumed value (0.086 versus 0.08).

The corresponding harmonics in the voltage waves of both rectifiers are comparatively small, so the harmonic powers also are small; the probable maxima at rated output are indicated in table V. For the 6-phase rectifier, it should be noted that all harmonics above the 17th are omitted; also, that a harmonic in the order of the 49th appears in the voltage waves, due to the supply system. For both rectifiers, the system reactance was about 20 per cent of the total, so the harmonic voltage drops therein and the resulting harmonic powers are somewhat greater than would ordinarily be expected in service.

### Meter Performance

The watt-hour-meter per-cent accuracies listed in table III have been corrected for minor errors in meter adjustment. For example, the actual test per-cent accuracies obtained for meter number 5 at 2.5 amperes in the sine-wave checks for both rectifiers were the same: 100.32, so 0.32 was subtracted from all test values. This procedure is equivalent to adjusting each meter to register correctly at its rated current of 2.5 amperes, in so far as comparative values are concerned. As just indicated, all results were carried out to the nearest 0.01 per cent and then rounded off to the nearest 0.1 per cent. The accuracy curves shown in figures 8 and 9 are quite flat and the differences between rectifier and corresponding sine-wave points are comparatively small.

Table V indicates that the probable maximum harmonic power for the 6-phase rectifier at rated output is about 0.6 per cent of the fundamental power; the corresponding values at 22 and 156 per cent output are 0.7 and 0.9 per cent, respectively. These apparent differences are not sufficient to account for the differences in effect on the meter speed. Although the phase relations of the several components of the harmonic power and therefore the true harmonic power itself at any output were not determined, there is no reason to expect that the net harmonic power changes sign as the rectifier output increases. In other words, there appears to be no correlation between the harmonic power and the rectifier effect. The probable maximum is less than 0.2 per cent for the 12-phase rectifier. It seems logical to conclude first, that the harmonic power due to 6- and 12-phase rectifiers will be comparatively small in practice and second, that their effect on the accuracy of modern watt-hour meters will be negligible.

### Var-Hour and Power-Factor Meters

The var-hour-meter results are given in table III. The accuracy curve shown in figure 10 is fairly flat at the higher rectifier outputs, but it turns down toward light load; the differences between rectifier and sine-wave points are, in general, greater than for the watt-hour meters.

Table III also gives the power-factor-meter readings (*a*) and these agree fairly well with the corresponding values (*c*) calculated from equation 2. In fact it appears to be satisfactory to use this formula even if, as in these cases, there is some harmonic power, providing the circuit is balanced. Similarly, it appears to be satisfactory to use the formula

$$\text{volt-amperes} = \sqrt{\text{watts}^2 + \text{vars}^2} = \sqrt{P^2 + Q^2} \quad (13)$$

to obtain the volt-amperes in the circuit,

**Table V. Probable Maximum Harmonic Power at Rated Output**

| Order of Harmonic | 6-Phase Rectifier* Per Cent of Line-to-Line Voltage | 6-Phase Rectifier* Per Cent of Line Current | 6-Phase Rectifier* Relative Harmonic** Volt-Amperes | 12-Phase Rectifier* Per Cent of Line-to-Line Voltage | 12-Phase Rectifier* Per Cent of Line Current | 12-Phase Rectifier* Relative Harmonic** Volt-Amperes |
|---|---|---|---|---|---|---|
| 1 | 100.0 | 100.0 | 10,000.0 | 100.0 | 100.0 | 10,000.0 |
| 5 | 1.7 | 17.7 | 30.1 | 0.2 | 1.4 | 0.3 |
| 7 | 1.1 | 8.8 | 9.7 | 0.1 | 0.5 | 0.1 |
| 11 | 2.2 | 5.1 | 11.2 | 1.3 | 5.0 | 6.5 |
| 13 | 2.8 | 3.9 | 10.9 | 1.1 | 3.8 | 4.2 |
| 17 | 0.6 | 1.8 | 1.1 | 0.2 | 0.4 | 0.1 |
| 19 | | | | 0.1 | 0.1 | 0.0 |
| 23 | | | | 0.3 | 0.9 | 0.3 |
| 25 | | | | 0.1 | 0.7 | 0.1 |
| Totals | | | 10,063.0 | | | 10,011.6 |

* Harmonic values taken from table IV (1), 6-phase rectifier values from test number 4.

** Relative harmonic volt-amperes at an assumed power factor of unity equals relative harmonic power in watts.

when not otherwise available. The ratio measured/calculated volt-amperes as obtained from equations 9 and 13, respectively, should approximate ratio (3) whenever the harmonics in the balanced voltage waves are small. This also applies to the ratio of power factors calculated from equations 2 and 1.

The average value of ratio (3) in 6-phase rectifier test numbers 1, 4, and 6a is 1.021 (from table IV, part 1). This compares with 1.025, which represents the average ratio for the same three tests between the two calculated power factors (table III, (c) and (b)). It appears that the voltage harmonics do not exert an appreciable effect.

It has been emphasized that the type *P*-3 power-factor meter is for use on balanced circuits only. In these tests, the circuit balance cannot be determined from the tables, as the averages of the voltages and currents instead of the individual values are given to conserve space. In general, excellent balance was obtained in the six-phase rectifier tests and in the corresponding sine-wave check tests, the maximum difference between any of the three voltages or between any of the three currents being in the order of one per cent.

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## Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

# Transient Analysis of Symmetrical Networks by the Method of Symmetrical Components


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**Synopsis:** The canonical equations of a general, linear, bilateral symmetrical network of $n$ meshes on which are impressed arbitrary mesh voltages are subjected to a Laplacian transformation. The transformed equations are then subjected to a symmetrical component transformation. By the use of these transformations the transient behavior of an $n$ mesh symmetrical network subject to impressed arbitrary voltages and initial currents and charges is readily obtained. The solution of the usual determinantal equation is avoided.


SINCE the introduction of the method of symmetrical components into electrical engineering by Fortescue in his classic paper,[1] there have been many extensions and expositions of the method.[2,3] It appears however, that no systematic exposition of the use of symmetrical components in the study of transients in linear, constant, bilateral symmetrical networks has appeared. It is the purpose of this discussion to present such an exposition. The methods of the Laplacian transformation and matrix algebra as presented in references 4 and 5 respectively will be assumed.

## I. The Canonical Equations

Let us consider a general, linear, constant, bilateral, lumped $n$-mesh network. Let the $n$ mesh currents have the instantaneous values $(i_1 \ldots i_n)$ and let there be $n$ voltages $(e_1 \ldots e_n)$ acting on the contours of the $n$ meshes. The canonical equations of such a general $n$-mesh circuit may be written in the form:

$$(e) = [Z](i) \tag{1}$$


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1. For all numbered references, see list at end of paper.

Where $(e)$ and $(i)$ are columnar matrices whose elements are the $n$ mesh voltages and currents respectively and $[Z]$ is a square matrix of the $n$th order whose elements are the various self and mutual impedance operators of the form:

$$Z_{rs} = L_{rs}d/dt + R_{rs} + S_{rs}\int_{-\infty}^{t}(\ )dt \tag{2}$$

and $L_{rs}$, $R_{rs}$, $S_{rs}$ are the coefficients of self- and mutual inductance, resistance, and elastance of the system. The impedance operator matrix $[Z]$ has the important property of being symmetrical about the principal diagonal. This property follows from the relations:

$$L_{rs} = L_{sr} \tag{3}$$

$$R_{rs} = R_{sr} \tag{4}$$

$$S_{rs} = S_{sr} \tag{5}$$

## II. E-Symmetric Systems

Many networks of practical importance have the property that their impedance operators satisfy the relations:

$$Z_{11} = Z_{22} = \ldots = Z_{nn} = Z_0 \tag{6}$$

$$Z_{sr} = Z_{jk} = Z \text{ for } r \neq s,\ j \neq k \tag{7}$$

that is, the impedance matrix of these systems has the form:

$$[Z] = \begin{Vmatrix} Z_0 & Z & Z & Z \ldots Z \\ Z & Z_0 & Z & Z \ldots Z \\ \ldots\ldots\ldots\ldots\ldots \\ Z & Z & Z & Z \ldots Z_0 \end{Vmatrix} \tag{8}$$

Such networks have equal self-impedance operators among the several meshes and also equal mutual impedance operators between the meshes. Networks exhibiting this type of symmetry are called *E*-symmetric and are of great technical importance. Symmetrical polyphase systems are of this type.

## III. The Laplacian Transformation of the Canonical Equations

Following the method of (5) part II, we subject the canonical matrix equation

(1) to a Laplacian transformation as follows:

Let

$$I_j(p) \div i_j(t) \qquad (I) \div (i) \tag{9}$$

$$E_j(p) \div e_j(t) \qquad (E) \div (e) \tag{10}$$

that is, for each element of the current matrix (I) and the voltage matrix (E) of (1) we introduce its Laplacian transform. Then the matrix equation (1) is transformed into:

$$[Z(p)](I) = (E) + p[L](i^0) - [S](q^0) \tag{11}$$

where:

$$(i^0) = \begin{Vmatrix} i_1^0 \\ i_2^0 \\ \cdots \\ i_n^0 \end{Vmatrix} \tag{12}$$

and $(i_1^0 \ldots i_n^0)$ are the initial mesh currents at $t=0$ in the system,

$$(q^0) = \begin{Vmatrix} q_1^0 \\ q_2^0 \\ \cdots \\ q_n^0 \end{Vmatrix} \tag{13}$$

$(q_1^0 \ldots q_n^0)$ represent the $n$ initial mesh charges at $t = 0$.

$$Z_{mn}(p) = L_{mn}p + R_{mn} + S_{mn}/p \tag{14}$$

$$[L] = [L_{mn}] \text{ the inductance matrix} \tag{15}$$

$$[S] = [S_{mn}] \text{ the elastance matrix} \tag{16}$$

## IV. Transformation to Symmetrical Components

In the theory of symmetrical components,[1] the transformations are effected by the use of the nonsingular, symmetric matrix:

$$[C] = [C_{rs}] \tag{17}$$

where

$r = 1, 2, \ldots n$

$s = 1, 2, \ldots n$

$$C_{rs} = a^{-(r-1)(s-1)} \tag{18}$$

$$a = e^{j2\pi/n} \tag{19}$$

The transformation matrix $[C]$, is thus a square matrix of the $n$th order with the important properties that:

$$[C]' = [C] \tag{20}$$

where $[C]'$ is the transpose matrix of $[C]$

$$[C]^{-1} = \frac{1}{n}[\text{conj } C] \tag{21}$$

where $[C]^{-1}$ is the inverse of $[C]$ and [conj $C$] is the conjugate of $[C]$. The rows of $[C]$ are the sequence operators of Fortescue.

Let us now multiply both sides of the equation (11) on the right by $[C]^{-1}$. We then obtain:

$$[C]^{-1}[Z][C][C]^{-1}(I) = [C]^{-1}(E) + p[C]^{-1}[L][C][C]^{-1}(i^0) - [C]^{-1}[S][C][C]^{-1}(q^0) \tag{22}$$

Now let us introduce the notation:

$$(E)_s = [C]^{-1}(E) \tag{23}$$

$$(I)_s = [C]^{-1}(I) \tag{24}$$

$$[Z]_s = [C]^{-1}[Z][C] \tag{25}$$

$$[L]_s = [C]^{-1}[L][C] \tag{26}$$

$$[S]_s = [C]^{-1}[S][C] \tag{27}$$

Then equation 22 may be written in the form:

$$[Z]_s(I)_s = (E)_s + p[L]_s(i^0)_s - [S]_s(q^0)_s \tag{28}$$

## V. Transformation of the E-Symmetric System

Let us consider the transforms of the equations of the $E$-symmetric system of part II. In this case, the impedance matrix has the form given by (8). Computation of the symmetrical component matrix of the $E$-symmetric system by the equation (25) gives:

$$[Z]_s = \begin{Vmatrix} [Z_0+(n-1)Z] & 0 & 0 \ldots & 0 \\ 0 & (Z_0-Z) & 0 \ldots & 0 \\ \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 \ldots & (Z_0-Z) \end{Vmatrix} \tag{29}$$

that is, the symmetrical component transformation matrix $[C]$, transforms the impedance matrix of the $E$-symmetric network into the diagonal form (29).

Let:

$$(I)_s = \begin{Vmatrix} I_{1s} \\ I_{2s} \\ \cdots \\ I_{ns} \end{Vmatrix} = [C]^{-1} \begin{Vmatrix} I_1 \\ I_2 \\ \cdots \\ I_n \end{Vmatrix} \tag{30}$$

and, similarly introduce the columnar matrices:

$$(E)_s = (E_{rs}) = [C]^{-1}(E_r) \tag{31}$$

$$(i^0)_s = (i_{rs}{}^0) = [C]^{-1}(i_r{}^0) \tag{32}$$

$$(q^0)_s = (q_{rs}{}^0) = [C]^{-1}(q_r{}^0) \tag{33}$$

then the equation (28) separates into the $n$ scalar equations:

$$[Z_0+(n-1)Z]I_{1s} = E_{1s} + p[L_0+(n-1)L]i_{1s}{}^0 - [S_0+(n-1)S]q_{1s}{}^0 \tag{34}$$

$$(Z_0-Z)I_{rs} = E_{rs} + p(L_0-L)i_{rs}{}^0 - (S_0-S)q_{rs}{}^0 \tag{35}$$

$r = 2, 3, \ldots n$

We then have immediately:

$$I_{1s} = E_{1s}/[Z_0+(n-1)Z] + p[L_0+(n-1)L]i_{1s}{}^0/[Z_0+(n-1)Z] - [S_0+(n-1)S]q_{1s}{}^0/[Z_0+(n-1)Z] \tag{36}$$

$$I_{rs} = E_{rs}/(Z_0-Z) + p(L_0-L)i_{rs}{}^0/(Z_0-Z) - (S_0-S)q_{rs}{}^0/(Z_0-Z) \tag{37}$$

$r = 2, 3, \ldots n$

Now if we let:

$$(i)_s \div (I)_s \tag{38}$$

that is:

$$i_{rs} : I_{rs} \tag{39}$$

$r = 1, 2, \ldots n$

We may compute the $i_{rs}$ quantities from (36) and (37). We also have the relations:

$$(I) = [C](I)_s \tag{40}$$

and

$$(i) : (I) \tag{41}$$

Hence if we premultiply (38) by $[C]$ we obtain:

$$[C](i)_s \div [C](I)_s = (I) : (i) \tag{42}$$

or finally,

$$(i) = [C](i)_s \tag{43}$$

and we have the various currents explicitly.

## VI. Examples

Let us consider the application of the above general theory to specific examples.

### Discharge of a Capacitor in One of Two Mutually Influencing Circuits

Suppose that we have two similar circuits each with self-induction $L_0$ and elastance $S_0$, but negligible resistance, and that the capacitor in one carries an initial charge $q^0$. The initial currents in the system and the charge on the capacitor of the second circuit are supposed to be equal to zero. The coefficient of mutual induction is $M$. The problem is to determine the subsequent behavior of the system.

In this case we have:

$$[Z] = \begin{Vmatrix} Z_0 & Z \\ Z & Z_0 \end{Vmatrix} \tag{44}$$

with:

$$Z_0 = L_0p + S_0/p \tag{45}$$

$$Z = Mp \tag{46}$$

Since we have no impressed electromotive forces and no initial currents, the equations (36) and (37) for this circuit reduce to the following:

$$I_{1s} = -S_0q_{1s}{}^0/(Z_0+Z) \tag{47}$$

$$I_{2s} = -S_0q_{2s}{}^0/(Z_0-Z) \tag{48}$$

in view of the fact that $n=2$ and $S=0$.

The transformation matrix $C$ and its inverse for this case is given by:

$$[C]=\begin{Vmatrix}1 & 1\\ 1 & -1\end{Vmatrix} \tag{49}$$

$$[C]^{-1}=\frac{1}{2}\begin{Vmatrix}1 & 1\\ 1 & -1\end{Vmatrix} \tag{50}$$

we thus have:

$$\begin{Vmatrix}q_{1s}^0\\ q_{2s}^0\end{Vmatrix}=\frac{1}{2}\begin{Vmatrix}1 & 1\\ 1 & -1\end{Vmatrix}\begin{Vmatrix}q_1^0\\ 0\end{Vmatrix}=\frac{1}{2}\begin{Vmatrix}q_1^0\\ q_1^0\end{Vmatrix} \tag{51}$$

since the second circuit does not have an initial charge. To simplify the operations, let us write:

$$M=L_0b \tag{52}$$

$$S_0=L_0c^2 \tag{53}$$

We then have the following equations for $I_{1s}$ and $I_{2s}$:

$$I_{1s}=-c^2pq_{1s}^0/[p^3(1+b)+c^2]=-\frac{1}{2}c^2q_1^0p/(1+b)[p^2+c^2/(1+b)] \tag{54}$$

$$I_{2s}=-\frac{1}{2}c^2q_1^0p/(1-b)[p^2+c^2/(1-b)] \tag{55}$$

If we now make use of the basic transform:

$$p/(p^2+w^2)\div \sin(wt)/w \tag{56}$$

we obtain:

$$i_{1s}=-\frac{1}{2}\frac{cq_1^0}{\sqrt{1+b}}\sin(ct/\sqrt{1+b}) \tag{57}$$

$$i_{2s}=-\frac{1}{2}\frac{cq_1^0}{\sqrt{1-b}}\sin(ct/\sqrt{1-b}) \tag{58}$$

The actual currents in the two circuits $i_1$ and $i_2$ are now obtained from the symmetrical-component currents $i_{1s}$ and $i_{2s}$ by the transformation:

$$\begin{Vmatrix}i_1\\ i_2\end{Vmatrix}=\begin{Vmatrix}1 & 1\\ 1 & -1\end{Vmatrix}\begin{Vmatrix}i_{1s}\\ i_{2s}\end{Vmatrix} \tag{59}$$

or hence:

$$i_1=-\frac{1}{2}cq_1^0[(1/\sqrt{1+b})\sin(ct/\sqrt{1+b})+(1/\sqrt{1-b})\sin(ct/\sqrt{1-b})] \tag{60}$$

$$i_2=-\frac{1}{2}cq_1^0[(1/\sqrt{1+b})\sin(ct/\sqrt{1+b})-(1/\sqrt{1-b})\sin(ct/\sqrt{1-b})] \tag{61}$$

We thus obtain the current in the two meshes without solving for the roots of the characteristic equation of the system which in this case is one of the fourth order.

### Application to Three-Mesh Network

Let us consider an $E$-symmetric three-mesh network. Let each mesh have a mesh inductance $L_0$ and mesh elastance $S_0$. Let the three meshes be coupled together by equal mutual inductance coefficients $M$.

The network will be considered inert at $t=0$, that is, the mesh currents and mesh charges are zero at $t=0$. At $t=0$, a steady electromotive force $E$ is impressed on mesh one. The problem is to determine the subsequent currents in the three meshes.

For this case, the impedance matrix of the network is given by:

$$[Z]=\begin{Vmatrix}Z_0 & Z & Z\\ Z & Z_0 & Z\\ Z & Z & Z_0\end{Vmatrix} \tag{62}$$

with:

$$Z_0=L_0p+S_0/p \tag{63}$$

$$Z=Mp \tag{64}$$

The general equations (36) and (37) in this case reduce to:

$$I_{1s}=E_{1s}/(Z_0+2Z) \tag{65}$$

$$I_{2s}=E_{2s}/(Z_0-Z) \tag{66}$$

$$I_{3s}=E_{3s}/(Z_0-Z) \tag{67}$$

Now, since the electromotive force impressed in mesh number 1 is steady, we have:

$$\begin{Vmatrix}E_{1s}\\ E_{2s}\\ E_{3s}\end{Vmatrix}=\frac{1}{3}\begin{Vmatrix}1 & 1 & 1\\ 1 & a & a^2\\ 1 & a^2 & a\end{Vmatrix}\begin{Vmatrix}E_1\\ 0\\ 0\end{Vmatrix}=\begin{Vmatrix}E_1\\ E_1\\ E_1\end{Vmatrix} \tag{68}$$

where:

$$a=e^{2\pi\sigma/3} \tag{69}$$

Hence we have:

$$I_{1s}=\frac{1}{3}E_1p/[p^3(L_0+2M)+S_0] \tag{70}$$

$$I_{2s}=\frac{1}{3}E_1p/[p^3(L_0-M)+S_0]=I_{3s} \tag{71}$$

Now if we let:

$$w_1=\sqrt{S_0/(L_0+2M)} \tag{72}$$

$$w_2=\sqrt{S_0/(L_0-M)} \tag{73}$$

then, in view of the transform relation:

$$p/(p^2+w^2)\div \sin(wt)/w \tag{74}$$

we obtain the following expressions for the transforms of $I_{1s}$, $I_{2s}$, and $I_{3s}$.

$$i_{1s}=\frac{1}{3}E_1\sin(w_1t)/\sqrt{S_0(L_0+2M)} \tag{75}$$

$$i_{2s}=\frac{1}{3}E_1\sin(w_2t)/\sqrt{S_0(L_0-M)}=i_{3s} \tag{76}$$

The actual three mesh currents of the system are now obtained by the equation:

$$\begin{Vmatrix}i_1\\ i_2\\ i_3\end{Vmatrix}=\begin{Vmatrix}1 & 1 & 1\\ 1 & a^2 & a\\ 1 & a & a^2\end{Vmatrix}\begin{Vmatrix}i_{1s}\\ i_{2s}\\ i_{3s}\end{Vmatrix} \tag{77}$$

Carrying out the matrix multiplication, we obtain:

$$i_1=\frac{1}{3}E_1\sin(w_1t)/\sqrt{S_0(L_0+2M)}+\frac{2}{3}E_1\sin(w_2t)/\sqrt{S_0(L_0-M)} \tag{78}$$

$$i_2=\frac{1}{3}E_1\sin(w_1t)/\sqrt{S_0(L_0+2M)}-\frac{1}{3}E_1\sin(w_2t)/\sqrt{S_0(L_0-M)}=i_3 \tag{79}$$

We thus obtain the solution to our problem in a most simple manner. It may be remarked that had we proceeded in the conventional operational manner, we would have been forced to determine the roots of a sixth order algebraic equation in order to apply the Heaviside expansion formula. A transformation to symmetrical components avoids all this labor.

## VII. Conclusion

The general equations by which the transient analysis of multimesh $E$-symmetric networks may be carried out have been developed. The introduction of symmetrical component and Laplacian transformations enormously simplify the analysis of this type of networks. Since $E$-symmetric networks are of great technical importance in many branches of engineering, it is hoped that this contribution to their theory will be of value. The method may be readily applied to all linear dynamical systems exhibiting this type of symmetry whether electrical or mechanical.

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## Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

# The Accuracy of Watt-Hour Meters on Intermittent Loads

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**Synopsis:** A watt-hour meter on intermittent loads of a particular character may have a registration error. The magnitude of error is a function of the meter design, the periodicity of the intermittent component of load, ratio of intermittent component to total load, character of intermittent component, power factor of load, and adjustment of the friction compensation.

The registration characteristic of a meter on most types of intermittent load can be predicted from the acceleration and deceleration curves for the meter disk.

THE characteristics of watt-hour meters are dependent upon many diverse factors interrelated in a complex way. The design of the magnetic circuits, the mechanical features of the meter, and the various corrective elements to a large degree are responsible for these diverse factors. Once in service, however, the characteristics of a meter are relatively fixed, except as influenced by the remainder of the circuits with which it is associated.

The nature of the load which is to be measured by the meter may have an important effect on the characteristic performance of the meter. Loads may vary continually in magnitude or be intermittent with the period of cyclic variation from a few cycles to many minutes or hours. Such intermittent loads may cause factors which are usually of relatively minor importance to have considerable influence on the meter accuracy. Since these factors are interrelated, it is difficult to separate them experimentally, and only their combined effects have been studied.

In the usual application of watt-hour meters, the intermittent nature of the load will affect only those factors which depend upon the magnetic effects produced by the current elements or series coils, the potential element being energized at all times, thus making its effects constant. However, some adjustments of the meter which are independent of the series coil may affect the meter performance because of the interdependence of those factors and their influence on the common sections of the magnetic circuit.

The results of this study are given in curve form and are representative of several meters operating under the same load conditions. A careful study of the starting and stopping characteristics was made photographically. These results were verified by actual load tests.

## Results of Study With Discussion

The registration of a watt-hour meter is a direct measure of the total angular travel of the meter disk. This angular travel, in turn, is a function of the angular velocity of the disk and time. The angular velocity of the disk for a given load is dependent upon the mechanical and geometrical factors of the moving system and the summation of the various component torques (driving and retarding) acting on this moving system.

It has been shown that the mechanical and geometrical factors for a given meter are essentially constant. As indicated in the appendix, the various component torques are constant when the load on the meter is constant, but for a variable load, the various component torques do not remain constant during the transitory periods. Certain torque factors which are present during the acceleration period of the meter disk may not be present during the deceleration period. The relative magnitudes of these changing torques will determine the meter accuracy during the transition period from one load value to another.

Figure 1 shows the accelerating and decelerating characteristic curves for a typical modern meter.* These curves are representative of those obtained from a stroboscopic photographic recording of the meter-disk travel during the period of change from rest to constant angular velocity and from constant angular velocity to rest. It will be noted that the slope of the constant-velocity sections changes in accordance with the different loads. Data for these curves were obtained by scaling angular travel of the meter disk from successive photographs of the disk obtained by means of a stroboscopic camera. The time interval between successive photographs was controlled accurately. The time or angular travel necessary for a disk to attain constant velocity was obtained by drawing a tangent to the curve at a slope corresponding to the velocity attained.

In an ideal meter in which no torque component is a function of higher than the first power of the disk angular velocity (appendix) and in which the ultimate disk velocity is directly proportional to the load, the time required to attain any given per cent of ultimate velocity is not a function of the load. In a practical meter, however, these conditions are not fulfilled although they are approximated closely. The position of the anticreep slots at the start of the acceleration period, the flux density in the various portions of the magnetic circuit, reactions of disk currents on the distribution of the flux in the various paths, and the variation of the friction torque with disk velocity are some of the factors which can produce small effects in a practical case. The accurate determination of the time required to attain steady-state condition is not necessary, an approximation being sufficient to indicate the character of intermittent loads which may give rise to registration errors. The graphical method of determining the point of tangency has inherent errors larger than the probable error due to the causes listed above.

The time required for the disks of meters of different designs to reach a constant angular velocity differs, the limits being approximately 0.2 second and 0.4 second. The time required for the disk to reach rest from the constant angular velocity corresponding to rated load is from 0.3 to 0.4 second. These variations between meters of different designs can be attributed to the fact that the components of torque are not in the same proportions in the different meters. It should be noted, however, that the time required is of interest only in the examination of a load cycle. The accuracy with which the meter integrates a load over a cycle depends upon the total disk travel during the cycle and not upon the time required for that travel.

If a constant load is placed on a meter

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* Both the modern and the older design of meters were used in the experimental tests.

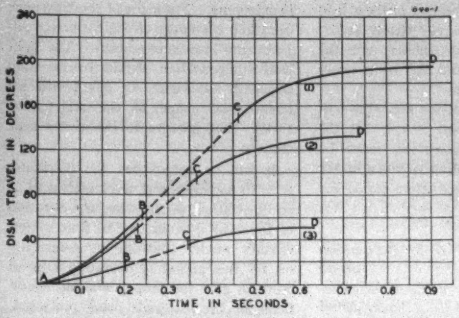



**Figure 1. Acceleration characteristics of a typical watt-hour meter for various loads at unity power factor**

A–B—Acceleration period
B–C—Constant-velocity period
C–D—Deceleration period

Curve 1—300 per cent load
Curve 2—250 per cent load
Curve 3—100 per cent load

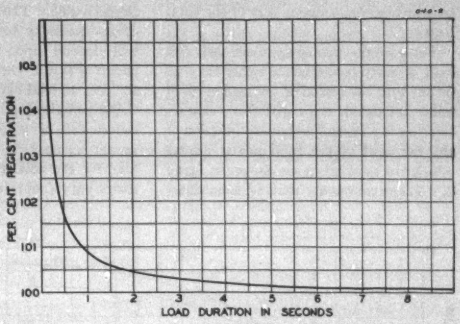



**Figure 2. Effect of load duration on watt hour meter accuracy for 200 per cent load a unity power factor**

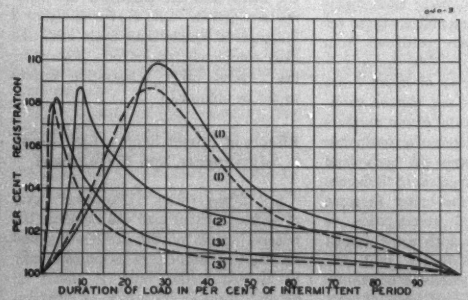
a sufficient time to allow the meter disk to start from rest and attain constant angular velocity and then is removed for the length of time required for the meter disk to return to rest, the total angular travel of the disk should be a direct measure of the energy involved in the load cycle. This total disk travel should be equal to the product of the constant velocity and the time the load is applied if this registration is a correct measure of the energy. During the period of acceleration up to the velocity corresponding to the load value, the disk has lost a definite number of degrees of travel since it must start from rest and its average velocity during this accelerating period is less than the constant value corresponding to this load. After the load is removed, the disk decelerates to rest and gains a definite number of degrees of travel. If the number of degrees lost during the acceleration period does not equal the number gained during the deceleration period the meter registration is in error. This error in registration will be positive or negative in accordance with too large or too small a gain in disk travel at the end of a load cycle compared to the beginning. It will be indicated later that this error is influenced by the design of the meter and its adjustments for constant load accuracy.

If the load exists for a longer time than is necessary for the disk to attain the velocity corresponding to the load, the disk will travel at constant velocity for the time in excess of that required to reach this load velocity. The disk travel to rest after the load is removed will be the same for a given disk velocity regardless of the time the meter has been running at this velocity. The error in registration (degrees of travel) will be the same for each load cycle, but the per cent error in total registration will approach that for a constant load.

The effect of the length of the constant velocity period on the total registration of the meter is shown in figure 2. This curve is obtained from curves such as given in figure 1. The curve of figure 2 is for approximately 200 per cent load, unity power factor on the meter. As the constant-velocity interval is increased for a given load, the per cent error is reduced. It will be noted that for load durations less than one second, the meter error, caused by intermittent load, is one per cent or more and, for very short duration loads, will exceed five per cent. If the load duration is greater than four seconds, the intermittent load cycle causes an error less than one-fourth per cent. This error is within the limits of commercial meter accuracy.

For practically all types of intermittent loads, the approximate registration characteristics of the meter may be predicted, from the acceleration and deceleration curves (figure 1) for the meter. These characteristics should be at the power factor and with the same wave form as would be encountered in the circuit under consideration. For any load-variation cycle in which the load decreases to zero the approximation may be very close if the acceleration curves are known for each value of load and the deceleration curve is known for the greatest value of load to be considered in the group of loads studied. The degree of approximation (in predicting the registration characteristics) for other load cycles depends upon the relative value of the variable and fixed components of the load. The approximation is least accurate when the fixed com-

**Figure 3. Comparison of predicted and test curves of watt-hour meter accuracy for intermittent loads of different periods**




Predicted curves are in solid lines
Test curves are in dotted lines

Curve 1—8-cycle period
Curve 2—35-cycle period
Curve 3—100-cycle period

ponent becomes a major part of the total load.

For a simple case of approximately full load of unity power factor either fully on or off, with the period of the load cycle of value indicated, the registration characteristics of a typical meter as a function of the per cent of the total period during which the load exists are shown in figure 3. These curves are derived from characteristics such as given in figure 1. Curves from experimental data for the same meter in a circuit with a load having periods of 8 and 100 cycles are shown for comparison.

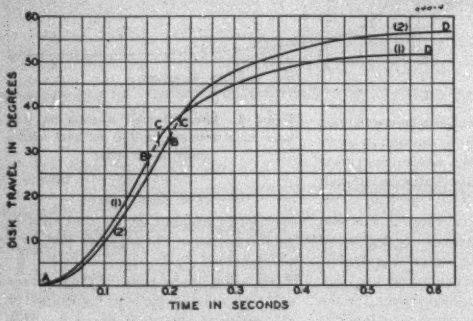



**Figure 4. Acceleration characteristics of a typical watt-hour meter for 200 per cent load at two different power factors**

With the characteristic curves for the meter available, for the loads chosen, such curves as those in figure 3 may, for simple load cycles, be predicted with ease. Beginning with the disk at rest the acceleration disk-travel curve is drawn for the length of time corresponding to the "on" portion of the load cycle. This curve is then extended by use of the deceleration disk-travel curve from the point on that curve having the same slope as the acceleration curve at the end of the first "on" portion. The deceleration curve is used for a time corresponding to the "off" portion of a load cycle. The acceleration curve is then applied as before except that the velocity at the end of the previous "off" period must be used to determine the initial conditions for the new "on" period. Successive "on" and "off" conditions must be assumed until the disk travel in any single load cycle becomes a constant value. This travel is compared with the proper value (constant velocity times the "on" time) and the registration noted as compared to the proper value. The number of these load cycles necessary to have "steady state" will depend upon the meter and the choice of load cycle and may be as many as 10 or 15 load cycles.

For complex load cycles the same procedure can be followed except that the proper characteristic curves must be used for the acceleration portions of the travel curve, and deceleration curves for partial removal of loads should be available. None of these deceleration characteristics for partial removal of loads has been included in the data of this investigation.

The experimental check was obtained by applying intermittent loads of a definite nature and comparing the actual registration of the meter for a known number of cycles "on" with the registration of the meter for the same number of cycles "on" for a continuous load of the same magnitude, power factor, and wave form. These check load cycles were chosen to correspond to those for which the errors were predicted from characteristic curves.

The predicted curves of figure 3 are for sinusoidal voltage and current variations. The experimental circuit currents correspond closely to that of a continuous welder. The harmonics in such load currents may be expected to influence the registration of the meter to some extent. Experimental investigation of this factor by the authors in the case of continuous loads indicates that the effects of such proportions of harmonics as are present in those load currents will not introduce an appreciable error in registration. The influence of this factor on the registration of a meter on intermittent loads should be very nearly the same as for constant loads having the same wave shape since the same torque factors would be affected by the harmonic components. For loads of short periodic duration, the effect of the corrective adjustments also is important. The light load compensation should be carefully adjusted, otherwise its effect will influence the shape of the registration curve. See paragraph (*b*) of the next section.

It will be noted that the maximum error in registration of the meter, used as an illustration, occurs when the duration of the load is from two to four cycles. Certain welder controls are commonly set for this period of operating time in order to give the proper working conditions for the materials being processed. It will be noted that the magnitude of the predicted maximum error is nearly independent of the period of load. This is borne out by the experimental results. Tests have indicated that, in the older designs of meters, this error is greater than in the more modern meter designs. This, no doubt, is caused by a different relationship between the various torque components in these classes of meters.

In some of the meters tested, when adjusted within the limits of accepted commercial accuracy, this maximum error was as great as 20 per cent. More than normal care in adjusting the meters resulted in the marked reductions in the maximum error.

The registration error due to intermittent load must approach zero as the acceleration portion of the load cycle approaches zero or 100 per cent of the load cycle. At some other value of the duration of load the error must be a maximum. The per cent of the intermittent period at which the maximum error occurs depends upon the design of the meter and the length of the intermittent period. The curves of figure 3 illustrate a simple load cycle with the load completely on or off. For other load cycles other registration curves would be obtained.

## Effects of Power Factor, Light-Load Adjustments, and Wave Shape

(*a*) *Power Factor.* The power factor of an intermittent load will influence the relative values of the accelerating and decelerating torques. This influence may be divided further into (1) effects on driving torque, (2) effect on friction-compensating torque, and (3) effect on current-damping torque. The exact influence of power factor on each is not known quantitatively but it may be shown (see appendix) that these three torque components may be affected. The driving torque per ampere will be

decreased as the power-factor angle is increased. This in turn may affect indirectly the friction compensation because of a new resultant flux per unit of driving torque. The new resultant flux may be shifted in time phase relative to the original flux, which may cause a change in the magnitude of the friction-compensating torque.

The effect of power factor on the current-damping torque is a function of current-coil flux. The flux will increase as the current increases but in a proportion which is dependent on the properties of the magnetic circuit. The effect at normal current values will be approximately in proportion to the current change per unit of power.

The net effect of small changes in power factor alone on the intermittent-load characteristic of the meter is ordinarily a minor one, because of the small net changes which occur in the total torques. Figure 4 shows the starting and stopping characteristic curves for a meter at two widely different power factors. The curve at the lower power factor indicates a longer time required to reach constant velocity from rest for the same load but the decelerating periods are the same. The elapsed time for a complete start-stop cycle is greater at the lower power factor and as a result the total travel of the disk is greater for the complete cycle. This increased time for a complete start-stop cycle will affect the meter performance on very short interval loads where the meter does not reach the true load velocity. For the loads of longer duration the error in starting and stopping is decreased and it is quite possible to have a meter with a combination of torque values which will give correct registration at some low power factor. Depending upon the adjustments of a meter, low lagging power factor loads may cause the registration error to become negative.

(*b*) *Light-Load Adjustments.* The curves which have been shown (figures 1, 2, 3, and 4) have been determined with the light-load adjustments as carefully adjusted as possible for all the meters used in these tests. The influence of this light-load compensation and how it can affect the meter performance on intermittent load is indicated by the registrations at three different positions of the light-load compensator for the same meter load. This influence is indicated in figure 5. The three points on the curve for this periodic load (three cycles on and five cycles off) are for the compensator positions of (1) ready to creep backward, (2) mid-position of compensator, and (3) ready to creep forward. The mid-position of the friction compensator corresponds very closely to the actual position used when this meter was in the original test circuits. Several test runs were made with the compensator at various positions and for intermittent loads of different periodic durations. It can be inferred from figure 5 that the component of torque from the compensator will be of great importance for loads of short periodic duration but will be less important as the period becomes longer. It is believed that more than ordinary care should be exercised in adjusting the compensator if the meter is to be used on a circuit which has a transitory load of major importance and of comparatively short periodicity.

(*c*) *Wave Shape.* Care was exercised in making comparisons between the performances for different load durations, that the wave shapes of the current and voltage were constant. The study of the effects of wave shape is separate and apart from this load study, but tests have been made which show that wave shape will influence the registration of a meter

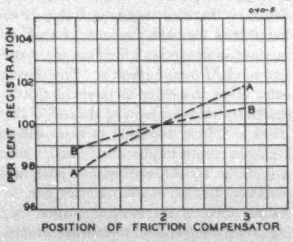



**Figure 5. Effect of friction-compensator position on watt-hour meter accuracy for intermittent loads of short duration**

*A–A*—One cycle on and seven cycles off
*B–B*—Three cycles on and five cycles off

and for that reason only performance curves for the same wave shapes were compared in determining the meter accuracy.

## Conclusions

1. The stroboscopic photographic data of the meter accelerating and decelerating characteristics can be used to predict with a good degree of accuracy the performance characteristics on most types of intermittent load. This is indicated by the comparison of the predicted and the actual test curve shown in figure 3.

2. The relative effects of the various torques influence the registration of a meter. If the speed of the disk is low, as in the present-day meter, the retarding torques will maintain a fairly uniform relationship. The current-damping torque has less relative effect in the modern meter and as a result, the accuracy on intermittent load has been improved.

3. The character of the load cycle, that is, the time the load is on and the time the load is off, influences the registration of the meter. Tests indicate that the conditions for maximum error occur at two to four cycles of accelerating period. This maximum error may be as much as 20 per cent. The off period apparently is not so important.

4. The adjustment of the light-load compensation is extremely important and care must be taken to be certain that there is minimum friction in the moving system of the meter, in order that friction-compensation-torque value may be minimized. If the adjustment is such that the meter is on the verge of creeping, an error up to 30 per cent may be obtained.

5. The variation of an intermittent load may be of a small magnitude in comparison with the average value of the load. In this case the influence of the load variation will be negligible.

6. Tests indicate that the load power factor influences the registration error. However, the damping effect of the current flux is relatively small in the modern meter, and the power factor of the load does not affect the meter accuracy on intermittent loads as much as in meters of older design.

7. The increased overload rating and increased ratio of driving torque to the moment of inertia of the moving element have decreased the accelerating time for a given load change. This improvement has decreased the meter error on intermittent load from the values found in the older designs of meters.

8. For metering loads which are continually transitory in nature, it is suggested that present-day meters be used and that a careful study of the load be made. Loads, such as electric welder and flashing electric-sign loads, should be carefully studied before being metered as a single load on a meter.

## Appendix

When a watt-hour meter is recording a constant load at a constant speed, the total driving torque equals the total retarding torque. The relationship can be expressed in equation form as:

$$(T_D+T_L)-(T_M+T_P+T_C+T_F)=0$$

where

$T_D$ = driving torque produced by the interaction of the potential-coil and current-coil fluxes
$T_L$ = driving torque of the light-load (friction) compensator
$T_M$ = retarding torque of the permanent magnets
$T_P$ = potential-flux retarding torque
$T_C$ = current-flux retarding torque
$T_F$ = retarding torque of friction

In order to indicate the relative importance and effect of each term the controlling factors of each torque are indicated. Thus, the torque equation becomes:

$$\underbrace{k_1 f[(f)\phi_P\phi_C \sin \alpha}_{1} + \underbrace{(f)\phi_P^2 \sin \beta]}_{2} -$$

$$\underbrace{\frac{k_1}{2} f_d[(f)\phi_M^2}_{3} + \underbrace{(f)\phi_P^2}_{4} + \underbrace{(f)\phi_C^2]}_{5} -$$

$$\underbrace{[k_f(f)f_d + F_0]}_{6} = 0$$

Part 1 = $T_D$ expressed as a function of potential flux, current flux, and the angle of displacement between them

Part 2 = $T_L$ expressed as a function of the square of the potential flux and the angle of displacement between the resultant flux and potential flux

Part 3 = $T_M$ expressed as a function of permanent-magnet flux

Part 4 = $T_P$ expressed as a function of potential flux

Part 5 = $T_C$ expressed as a function of current flux

Part 6 = $T_F$ expressed as a function of disk speed plus a friction-torque component independent of speed

$k_1$ = constant which includes the geometrical constant, gravitational constant, etc.

$f$ = circuit frequency

$f_d$ = rotational speed of the meter disk

$k_f$ = frictional constant for the disk

$F_0$ = friction constant

During the interval of transition from one load value to another, the torque equation must contain another term. This term, which may be called the transition torque, may be a driving or a retarding torque and will be of sufficient magnitude to balance the torque equation at every instant. The transition torque will be a retarding torque during an increase in load and a driving torque during a decrease in load. The rate of change of the transition torque during a transition interval will depend upon the changes in the other components in the torque equation. Since the retarding torques are a function of disk speed and the meter registration is $\int f_d dt$, the meter registration for loads which are for the most part transitory in nature, will depend on the effect of the transition torque.

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## Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

# Induction-Motor Characteristics at High Slip


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THE practical work of inventing the polyphase induction motor, by Nikola Tesla and Galileo Ferraris, was followed by farseeing analytical studies of motor operation. Masterly theoretical analyses of the induction-motor circuit were made by B. A. Behrend, Alexander Heyland, and others. These men, through their insight and understanding, were able to devise ingenious methods for theoretically predetermining operating characteristics of induction motors by employing readily determined constants. For many years these methods of predetermination were accepted and used in practical work. However, as knowledge has expanded and a higher degree of accuracy becomes requisite, it has been found that the older methods of analysis produce inaccuracies which are too great for modern requirements. The trend away from the older methods is clearly shown by abandonment of the use of the classical "circle diagram" in cases where highly accurate results are desired. The use of the former methods of predetermination results in inaccuracies due to several factors, the most important being: (*a*) unjustified treatment of the exciting current, (*b*) the assumption that circuit parameters are constant when they are not, and (*c*) failure to consider the stray load loss. The errors resulting from wrong assumptions may not prove serious for light loading of the motor, but discrepancies increase as load and slip become greater.

A study is made in this paper of the factors which produce rotor losses and corresponding torque in induction motors. A method of accurately analyzing this problem is given, based upon elemental principles and including important effects which have been omitted from previous studies. In order that correct principles may be applied and accurate results obtained in practical determinations, a complete test procedure with required calculations is outlined. The principles developed are illustrated by tests on a selected motor. However, these principles are general in nature and are not limited in their application by the type or size of induction motor. In approach and general treatment of the subject the analysis differs from previously accepted methods. This difference is pronounced in two important respects. In the first place, the analysis gives consideration to the effects of stray load loss. In order to predict results the laws of variation of this loss are investigated and it is shown that it varies as the square of both current and motor speed. The fact that this loss plays a highly important part in the production of motor torque at all higher values of slip is made clearly evident. Secondly, a study is made of the rotor-resistance loss, showing that variations in the value of rotor resistance become a most important factor in such considerations. In this connection, the rotor effective resistance is studied and its variation with the frequency of the rotor circuit is determined. The manner in which the resulting loss operates to produce motor torque is shown clearly by the analysis. Finally, the net over-all torque is derived by combining the separate components. The results show great discrepancies when compared with conventional values.

Investigation of induction-motor characteristics was made over a range of slip extending from zero up to a value of 200 per cent. Accurate determinations show that the actual torque of a motor at high slip may have a value of two or three times that calculated by conventional methods. Discrepancies of this nature have been noted by other investigators[1] and are of such magnitude as to demand


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1. For all numbered references, see list at end of paper.

attention. In modern applications a motor may be reversed by plugging, at which instant the slip is 200 per cent. In such reversing cycles both the heating of the motor and the torque developed throughout the cycle become important considerations. The extent of the heating is determined by the magnitude of the losses and the time required to reverse the motor, the latter depending upon the torque developed. The magnitude of instantaneous torque also becomes an important factor in shaft design. In addition, the results of the investigations with which this paper is concerned have a direct application in problems of polyphase unbalance. In applying the symmetrical-component method of analysis, the action of the negative-sequence current is made truly predictable through the application of the principles herein deduced.

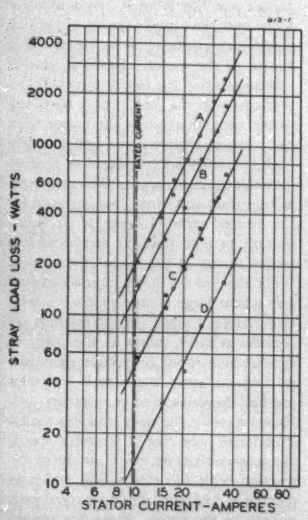



**Figure 1. Curves of stray load loss as a function of stator current for different rotor speeds**

| Curve | Rotor Speed in Per Cent of Synchronous Speed | Rotor Frequency (Cycles Per Second) |
|---|---|---|
| *A* | 100 | 120 |
| *B* | 80 | 108 |
| *C* | 50 | 30 and 90 |
| *D* | 25 | 75 |

## Experimental Investigation

In order to make a practical study of motor characteristics, tests were made on an ordinary squirrel-cage induction motor. To insure that the effects of stray load loss would not show themselves in undue proportion, a motor was selected in which this loss was reasonably low, being 2.08 per cent of full-load input at rating. It was fortunate that considerable test information was already available, this motor having been used in previous tests.[3,4] The motor was rated at ten horsepower, 550 volts, 10.3 amperes, three phase, 60 cycles, and 1,750 rpm. The stator had 48 teeth with semiclosed slots, and the rotor 57 teeth with coffin-shaped slots.

The motor was directly connected to a calibrated d-c machine by a flexible coupling. Power from a three-phase a-c source, having balanced voltage which could be adjusted to any required value, was applied to the stator. Instruments were so arranged that both electrical power input and output could be accurately measured. Measurements were taken at several values of current while the speed was held constant and observed by the use of a stroboscope. Motor current was adjusted to any desired value by control of the applied three-phase voltage. Measurements were made over a range extending from rated current to between three and four times this value. The stator resistance was measured by a resistance bridge immediately following each run, and the friction and windage loss of the two coupled machines was measured at the same time by driving through the d-c machine. Complete runs were made for speeds of 100, 80, 50, and 25 per cent of synchronous speed in the reverse direction to the stator field, for zero speed with locked rotor, and for 25, 50, and 80 per cent of synchronous speed in the same direction as the stator field.

## Stray Load Losses

For all points at synchronous speed in the reverse direction values of stray load loss were calculated by the reverse-rotation method.[4] Each point was obtained by taking the difference between the net mechanical power input to the rotor and the net electrical power input to the rotor received from the stator. The results are shown by curve *A* of figure 1 where the loss is plotted as a function of stator current on logarithmic cross-section paper. Curves *B*, *C*, and *D* in this figure show the stray load loss for speeds of 80, 50, and 25 per cent of synchronous speed respectively. The three latter curves are obtained in the same manner as curve *A* except that care is taken to subtract the appropriate value of net rotor power supplied by the stator for each speed. These amounts are 0.8, 0.5, and 0.25 times the rotor power received from the stator for corresponding speeds.

The black points of curve *C* were obtained by operation of the machine at 0.5 speed in the same direction as the stator field (that is, for ordinary motor action). In this case the stray load loss is obtained by subtracting the measured value of net mechanical power developed from one-half of the rotor power received from the stator. The close agreement between values obtained in this manner with those obtained from reverse rotation at the same rotor speed indicates the degree of accuracy of the reverse-rotation method at this particular speed. This substantiates the assumption that the stray load loss is not affected by the direction of rotation.

Curves *A*, *B*, *C*, and *D* of figure 1 all have a slope of two indicating that the stray load loss varies as the square of the current for all values of speed.

In order to determine the law of variation of stray load loss as a function of motor speed, values of the loss at different speeds were taken from the curves of figure 1 at the point of rated current. In figure 2 these quantities are plotted as a function of motor speed on logarithmic cross-section paper. The fact that the resulting curve has a slope of two indicates that the stray load loss varies as the square of the rotor speed for constant current.

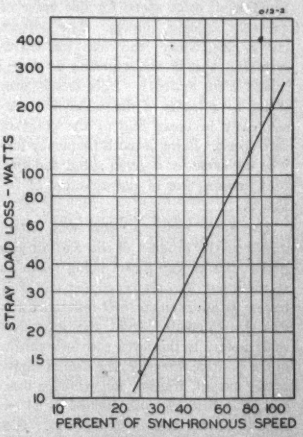



**Figure 2. Stray load loss as a function of speed at rated current**

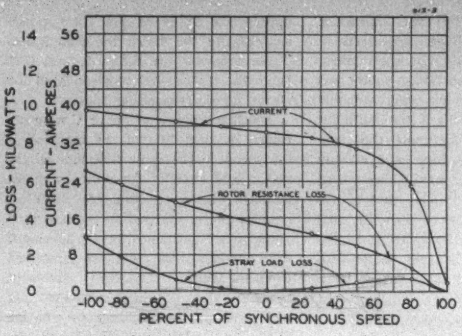



**Figure 3. Stator current and losses at one half voltage as function of rotor speed**

## Motor Characteristics at One-Half Voltage

Since it was impossible to obtain measurements at full voltage for the speeds selected without damaging the motor due to overheating, the characteristics of the motor were first obtained at one-half rated voltage. The top curve of figure 3 shows measured stator current as a function of rotor speed for this value of constant applied voltage. The bottom curve gives stray load loss for corresponding speeds and currents as determined from figure 1. This loss is produced by rotation of the motor and consequently becomes zero at the point of zero speed. Being a tooth-frequency loss it is the same for a given speed and current, irrespective of the direction of rotation.

The rotor resistance loss was determined as the product of slip and air-gap power, the air-gap power being taken as stator input less stator copper and iron losses. In addition the rotor resistance loss was also calculated from the measured shaft power. In this latter case for rotation in the positive direction, the sum of shaft-power output, friction and windage loss, and stray load loss was divided by (1 — slip) to obtain the air-gap power. For rotation in the reverse direction the sum of friction and windage and stray load loss was subtracted from the mechanical power input to the shaft and the difference divided by (slip — 1) for obtaining air-gap power. The fact that the values of the rotor resistance loss obtained from the stator electrical power input and from the mechanical shaft power showed good average agreement indicated that the iron loss due to the stator leakage flux was of negligible importance for these calculations.

The rotor resistance loss thus obtained is of the nature of an *effective* resistance loss and includes all components of loss that occur as a result of the slip-frequency rotor currents. In addition to the slip-frequency copper loss component, there may be components of eddy-current losses in the rotor circuit and slip-frequency iron losses caused by the air-gap and rotor-leakage fluxes. This effective resistance loss of the rotor is shown by the middle curve of figure 3.

Each loss produces its own value of torque. The rotor effective resistance loss results in a force from the reaction of slip-frequency currents in the rotor and the air-gap field rotating at synchronous speed. Thus the torque can be calculated from the power loss and the difference in speed of the rotor and the synchronous field (that is, the slip speed). The dashed-line curve of figure 4 shows the torque resulting from the rotor effective resistance loss. At small values of slip a small loss produces a large torque while at high slip it takes a large loss to produce the same torque. The torque resulting from the rotor resistance loss is the only component of torque which in the past has been considered in conventional calculations. The curve of rotor resistance loss shown in figure 3, and corresponding torque of figure 4 differ from customary calculations in that they are derived from actual measurements, instead of being calculated from a value of rotor resistance which is usually considered as constant.

The stray load loss produces a drag on the rotor which in this respect is similar to friction and windage effects. Thus the torque resulting from it has a negative value over the complete range of positive directional speeds, reducing the available torque of the motor. However, during reverse rotation the torque from this loss tends to stop the motor, thus operating in the same direction as the torque from the rotor resistance loss. Consequently both quantities are considered as positive over this range of speeds. The torque resulting from stray load loss is shown by the bottom curve of figure 4. It is important to note that the stray-load-loss torque occurs at the speed of the rotor. While this loss (as shown in figure 3) does not appear large it may produce a relatively larger torque. If for example we consider relative values at the point of synchronous speed in reverse direction, we find the stray load loss is less than one-half the value of rotor resistance loss. However, while the stray load loss results from forces occurring at the rotor speed, the rotor resistance loss is produced by reaction with the stator field which is moving at double synchronous speed with respect to the rotor. Since the torque for any rotor loss varies inversely as the speed of the force reaction producing it, the difference in speed results in torque from the stray load loss which is nearly equal to that from the rotor resistance loss at this point.

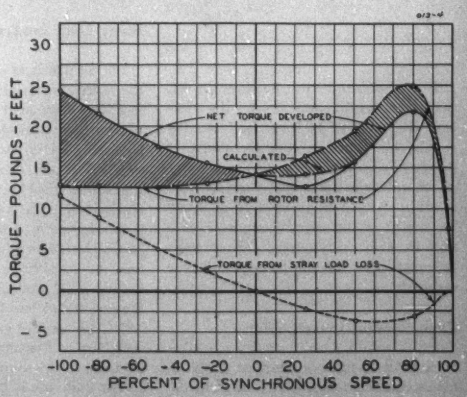



**Figure 4. Torque curves for one-half-voltage operation**

The combination of the torque from stray load loss with that from the rotor resistance loss gives the net torque available to drive the rotor. Stray load loss causes a reduction in torque over the range of direct rotation which is shown by the shaded portion to the right of the point of zero speed in figure 4. For reverse-rotation operation the torque from stray load loss causes a marked increase in the net torque tending to stop or reverse the motor. This effect is shown by the shaded portion at the left of the diagram. It is significant that the measured shaft torque, after being corrected for friction and windage, gives a net value which is in complete agreement with the resultant of the two components, with the exception of a short portion of the curve between zero and one-half speed in the positive direction. The discrepancy over this range is considered to be the result of torque effects caused by harmonic components of flux. The full-line curve marked "net torque developed" in figure 4 was obtained from measured output.

## Rotor Effective Resistance

All losses which occur at slip frequency in the rotor have been considered as rotor *effective* resistance loss. This loss was found to vary as the square of the current for a given frequency but to have different values for the same current at different frequencies. This indicates that the effective resistance of the rotor is not constant. Its value for one phase of an equivalent wye-connected rotor was obtained by dividing the total loss by three times the square of the rotor current. The equivalent effective resistance for each phase of the rotor circuit is shown by the curve of figure 5. Since the total loss includes among its components hysteresis and eddy-current iron losses due to the rotor leakage flux, it could not be expected that the effective resistance would remain constant at different rotor frequencies.

The curve shows that the rotor resistance increases appreciably at higher frequencies, being about 1.68 times as large at 120 cycles (synchronous speed in reverse direction) as it is at very low frequencies. At zero speed (locked rotor) the resistance has risen to 1.18 times its lowest value.

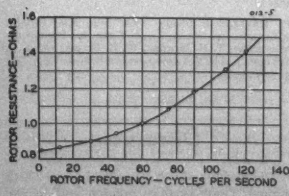



**Figure 5. Curve of rotor resistance per phase as a function of frequency in the rotor circuit**

It was found that the resistance could be expressed by a mathematical equation of the following general form

$$R_{eff} = a + b\epsilon^{mf}$$

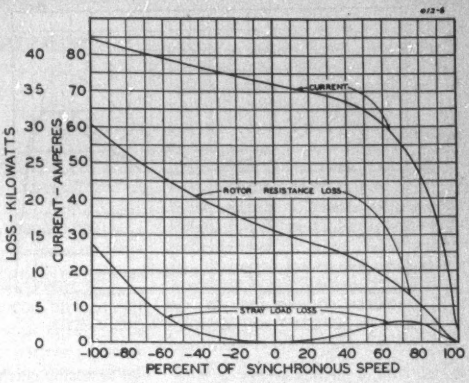
where $R_{eff}$ is rotor effective resistance in ohms per phase, $f$ is frequency in cycles per second, $\epsilon$ is the base of natural logarithms, and $a$, $b$, and $m$ are constants. Supplying values of the constants for this particular case gave the equation

$$R_{eff} = 0.74 + 0.103\epsilon^{0.0188f}$$

## Characteristics at Full Voltage

Knowing the value of rotor effective resistance and the laws of variation of stray load loss with current and frequency, motor characteristics at full voltage can be easily calculated if current values can be determined. The latter were obtained by extrapolation of current-voltage curves taken at constant speed. A slight curvature in such curves, extending up to a point of approximately twice rated current, indicated small effects due to tooth saturation. For higher values of current the curves become straight lines permitting accurate extension to the point of rated voltage. Current values obtained in this way are shown by the top curve of figure 6. The rotor resistance loss then was calculated using values taken from figure 5, and the stray load loss was obtained by extrapolation of curves of figure 1. The resultant loss curves are also shown in figure 6.

**Figure 6. Curves of current and losses at full voltage**




Torque values corresponding to each of the losses were obtained in the manner previously described for the one-half voltage characteristics. The resultant net torque curve was then found by combining the torque components as in figure 4. This net torque developed at full voltage is shown by the full-line curve of figure 7. Stray load loss has a more pronounced effect in altering the torque curve at full voltage than at one-half voltage due to the fact that this loss and its corresponding torque vary as the square of the current. The full-voltage torque curve is obtained on the assumption that both rotor and stator resistance remain unchanged from heating by the high currents, which would not be the case if such currents were maintained for more than a very short period. This torque curve is quite accurate except over the range of motoring speeds extending from zero to approximately one-half synchronous speed. Over this range harmonic fluxes may cause changes in torque which are difficult to predict.

In order that this speed-torque characteristic might be compared with the curves calculated in the conventional way from constants measured under locked-rotor conditions the latter are also given. The dotted-line curve marked "theoretical—$A$" is derived from circuit parameters measured at zero speed with current corresponding to the point of rated voltage. Consequently it agrees with the actual curve at this point. The dashed-line curve labeled "theoretical—$B$" is computed from locked-rotor circuit parameters taken at the point of rated current. The rotor effective resistance was the same for these two cases, but the combined leakage reactance was larger for the case of rated current. This latter difference was due to magnetic saturation

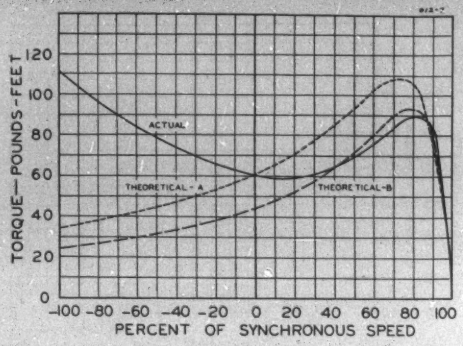



**Figure 7. Comparison of actual torque to be expected with torque curves computed from locked-rotor measurements**

in the path of the leakage flux as above mentioned. This difference in value of leakage reactance produces very different theoretically computed speed-torque curves. However, the important fact to note is the pronounced difference between the actual torque and that obtained by calculations from locked-rotor data. At synchronous speed in the reverse direction the actual torque developed is more than three times that computed by conventional methods.

### A New Accurate Method

The ability to obtain accurate characteristics of induction motors without actually measuring them is most desirable. It is evident that if such predetermination is to be made it will require more information than can be obtained from locked-rotor and no-load tests. The effects of stray load loss and the variation of rotor effective resistance as a result of change in rotor frequency must be taken into consideration. These effects may be included readily by adopting the following procedure.

In addition to the customary locked-rotor and no-load tests two additional tests become necessary. These are a reverse-rotation test and an ordinary load run. The reverse-rotation test has been fully specified in a previous paper[4] which should be referred to for a complete description. This test, which is made at synchronous speed in reverse direction, should include data over the range of current from rated value up to as high an amount as can safely be used without overheating the machine. The test will give stray load loss as a function of current at synchronous speed. By application of the law that this loss varies as the square of current and speed its value can be calculated for any required condition. The rotor effective resistance loss can be readily obtained by taking twice the air-gap power for points of test. Knowing the resistance loss for given values of current the rotor effective resistance can be calculated readily at double frequency. A current-voltage curve can also be plotted, which when extended as a straight line above the point of saturation will give the current for rated voltage.

The locked-rotor test would be made as in the past over as large a range of current as possible. The results should be shown in a current-voltage curve which may be extended as above to the point of rated voltage. Impedance per phase can be calculated from voltage and current at this point. Then by using the average value of input effective resistance a value for total inductive reactance can be obtained. Measurement of stator resistance will permit determination of the rotor resistance by separation.

An ordinary load run should be made in which the slip is measured with high accuracy. Output power is not an important measurement as air-gap power can be obtained by subtracting stator copper and iron losses from measured input power. Multiplication of air-gap power by slip will give the rotor resistance losses. Rotor current is found by vector subtraction of the exciting component from the stator current. Rotor resistance per phase is then computed from rotor losses and rotor current.

We now have three points of rotor effective resistance, that is, points at low rotor frequency, locked rotor, and double frequency. This will permit the drawing of a curve of rotor resistance similar to that of figure 5. It now remains only to find current values for rated voltage in order to determine rotor resistance loss and stray load loss. Current at no load and at rated load has been obtained by measurement. Also, values of current are available for the locked-rotor point and for that of synchronous speed in reverse direction. This leaves points of current between that of zero speed and full load to be determined. Values of rotor resistance over this range are available from the curve. By assuming values of slip and dividing the corresponding rotor resistance by it we obtain the equivalent circuit secondary resistance. The total input resistance is obtained by addition of primary resistance to secondary equivalent resistance. This may be combined with the input reactance obtained from the locked-rotor test to find the total input impedance. It has been found that leakage reactance remains nearly constant over this range of speeds, but any slight variation therein is not serious because of the greater importance of the rotor equivalent resistance. Knowing the equivalent impedance, current values can then be calculated for any given speed. As the current curve appears to be almost a straight line between zero speed and synchronous speed in reverse the complete current curve can now be drawn. Loss curves can be determined and corresponding torque curves obtained. Resultant torque is then found by combination of the component values. The experimental work necessary to obtain accurate determinations as above described is not increased greatly over that required for conventional determinations, the main additions being the reverse-rotation test and the measurement of slip for a corresponding value of power input under load. Calculations are simple and straightforward with the separate steps following in a logical manner.

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## Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

# Control of Inductive Interference to Telegraph Systems

J. W. MILNOR
FELLOW AIEE

THE tendency of power-supply and distribution systems to cause extraneous currents to flow by induction into telegraph lines has presented a diversity of problems which are of concern to both interests. No one solution is found to be of general application; rather it ordinarily is necessary that each situation be made the subject of individual study.

In different instances it may be most economical to control the interference by attention to the design of the power system, or by choice of routes for each line, or by mitigative equipment applied directly to the telegraph system. The present paper will be limited in scope to the third class of control methods; it will describe various special devices which may be applied in different cases to the telegraph circuit for reducing the power interference, with indications of their accomplishments and of their limitations.

The discussion herein is in particular reference to interference which tends to continue during normal working of the power systems, although some of the devices referred to are also effective in removing those more severe surges which occur at times of power line or equipment failures. Extraneous voltages are induced where power and telegraph lines parallel, and tend to reduce the capacity and the dependability of the telegraph. An exposure one mile in length at a separation of a few hundred feet may result in a small or a severe interference dependent upon the nature of the power system and type of telegraph circuits. The voltages are caused by the magnetic field created by the power system, which interlinks the telegraph wires. The electric field from the power line is seldom of importance.

Usually the fundamental frequency of the power system, 25, 50, or 60 cycles, is of chief concern. Sometimes the third harmonics of these create interference. In our experience no cases have occurred where harmonics higher than the third have created interference to physical telegraph circuits. The interference is most severe where some part of the power current flows in the earth, as may be the case when neutral points are grounded, or as always occurs in electric-railway practice.

As distinct from power practice the telegraph circuits ordinarily are not worked at any standardized frequencies. The assigned speed of each telegraph depends upon the amount of business between the terminuses; economical considerations require that where the business is sufficient to justify, the speed shall be the maximum practical working capacity of the line between the points.

The consideration that in this country there are many situations where large volumes of telegraph business exist between cities widely separated, has created a strong incentive to develop the maximum telegraph line speeds. As part of this objective Western Union has endeavored to survey every practical method for minimizing the effects of power induction.

## Review of Theory of Telegraph Transmission

The transmission of intelligence by telegraph requires that current, controlled in accordance with a code and representing the message to be sent, shall be impressed on the line and shall be correctly interpreted at the distant end of the line. The discussion herein will be in particular reference to the multiplex printing telegraph system, which serves for the more important message circuits and which utilizes probably the most efficient available code. However, the fundamental problems of line transmission are the same in all telegraph systems.

In the multiplex each letter or figure is represented by a code character consisting of five units of time. During each time unit there is applied to the line either positive or negative battery as indicated in figure 1, the battery ordinarily being of 160 volts. No space occurs between consecutive characters. A measure of the speed of the circuit is the "dot frequency" or the "fundamental signaling frequency" of the circuit, which is the reciprocal of the time required for two consecutive units in the code character.

During its passage along the line the telegraph signal becomes rounded and the current becomes weakened. The practical working circuit speed is limited by the amount of weakening of the signal which can be tolerated in the presence of such extraneous currents as then exist. Any induced currents from external sources are of course superposed on the received telegraph current, and amounts of induction exceeding about six volts are sufficient to cause a measurable impairment of the telegraph.

In field measurements of telegraph transmission it is customary to examine the current sent and received, and the rate of change of the current between reversals. However, for analytical purposes it often is useful to regard the circuit as an a-c transmission system. While telegraph transmission would appear superficially to be wholly different in principle from that of power supply, there is only this basic difference, that while the power supply system need transmit one frequency only, the telegraph circuit must be capable of sending a band of frequencies the lower limit of which is zero frequency and the upper limit of which is somewhat above the dot frequency.

If in the telegraph transmitter a given combination of signals is set up and is

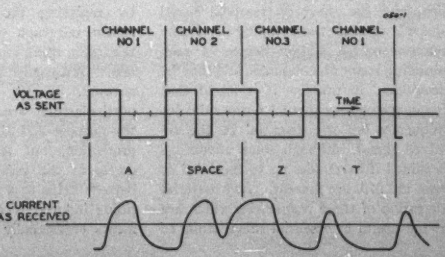


Figure 1. Typical signals in three-channel multiplex printing telegraph system

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repeated over and over, the combination may be analyzed by well-known methods into the sum of a number of sinusoidal waves of definite frequencies. In figure 2 are shown the frequencies contained in certain signal combinations when repeated again and again. Values above 200 cycles are not shown, although actually they continue with decreasing amplitude to infinite frequency.

Commercial telegraph traffic, of course, is made up of random reversals of voltage rather than of recurring signal combinations. In strictly random traffic the frequency spectrum is found to be continuous, that is, it contains substantially *all* frequencies from zero upwards, rather than certain discrete frequencies.

If the telegraph circuit were to transmit all frequencies without reduction in amplitude and in correct phase, the received signal would be identical to that sent. In practice the upper frequencies are reduced or removed in traversing the line, and the effect on received signal shape is to cause the rounding previously referred to. A certain degree of such rounding is not objectionable and may be desirable. In practice it is found that frequencies above about 1.6 times the dot frequency are not essential in the received signal, although some advantage is gained if harmonics up to the third or even the fifth are present. Any material alteration of those frequencies which are in the useful or essential range tends to cause distortion or mutilation of the received signals.

## Devices for Separating Power Induced Voltages From Telegraph

Once extraneous voltages have been induced from a power system into telegraph, their removal is difficult only because of the need for minimizing any direct impairment to the telegraph. Equipment for removing the interference must not introduce any material added impedance into the telegraph nor remove any essential components of the telegraph currents, otherwise its objective is defeated. Among telegraph circuits carried along a common route there ordinarily is some tendency to induce currents known as "cross fire" into each other; the equipment for removing power interference must not increase such cross fire.

Interference of course can be removed by replacing the customary ground-return telegraph circuit by a metallic telegraph, using two line wires instead of one. Or a carrier telegraph may be substituted. Placing the wires in cable, particularly if armored, is effective for the purpose and also affords mechanical protection, but is expensive. An increase in the voltage of the telegraph battery helps to a small extent in overriding induced voltages. Such arrangements occasionally may be justified to reduce power interference, but hardly can be considered to be a general solution as a co-ordinative measure.

Devices for removal of induced power voltages are of two general classes. In the first a pilot wire set aside for the correction, is placed on the pole line carrying the telegraph wires and extends throughout the length of the exposure to power. The second class of devices depends upon tuning to remove the sinusoidal power current.

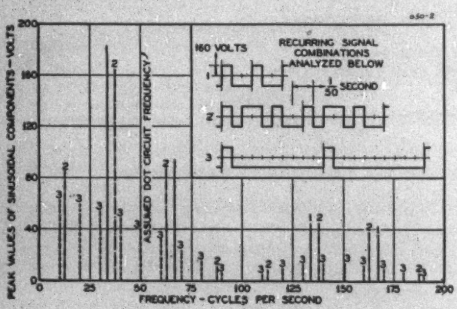


Figure 2. Examples of analyses of repeated telegraph signals into their sinusoidal components

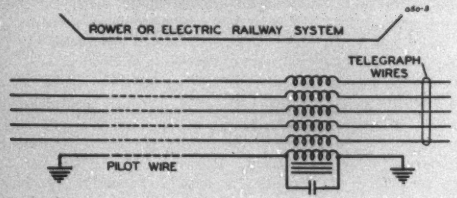


Figure 3. Multiwire neutralizing transformer

## Mitigative Systems Including a Pilot Wire

The pilot wire is exposed to the same induced voltage as the telegraph wires. This is conducted by the pilot wire into suitable equipment which in turn applies to the telegraph wires a voltage to neutralize the interference.

### Neutralizing Transformer

Illustrated in figure 3, this is a relatively simple device which under suitable conditions is fairly effective. In one form it was used early by Professor C. F. Scott. All wires on the pole line may be corrected simultaneously, all transformer coils in the multiwire transformer being wound on the same iron core.

As at present developed the step-up ratio is only slightly above unity, and the inductance of the primary winding is tuned to the disturbing frequency. To prevent partial saturation of the core by currents in the telegraph wires, an air gap is included in the core. The correction of voltages up to 200 in an exposure 20 miles in length, has been obtained with a transformer weighing 500 pounds, in as many as 34 wires carried on the same pole line. The removal of power interference is nearly perfect unless limited by conditions such as local earth potentials at the grounding points, but the system tends to add cross fire between the various telegraph circuits.

As in all other correcting systems it is necessary to examine the direct effect of the transformer on the telegraph currents. The transformer adds impedance in each telegraph wire, but more important is the cross fire induced between

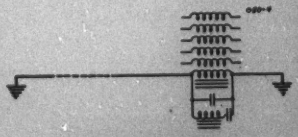


Figure 4. Neutralizing transformer for correction of two frequencies

the various wires. These effects may be controlled by holding to a low value the resistance of the primary circuit. That is, a mutual impedance exists between each pair of telegraph circuits, which may be considered to consist of an inductance shunted by the capacitor and by the primary circuit. The resistance of the latter including the wire and its earth connections should not exceed 40 ohms and preferably should be lower. To this end there have been used pilot wires as large as number 3 Brown and Sharpe gauge, with earth connections made of a dozen paralleling grounding pipes. The limitation in resistance obviously sets a limit on the length of exposure in which a multiwire neutralizing transformer can be used economically, where high-speed telegraph circuits operate.

If the telegraph circuits are worked at low speed, or if a separate pilot wire is provided for each telegraph circuit, the limitation as to length becomes less difficult. Individual line neutralizing transformers have been used in exposures up to 60 miles in length using a pilot wire of number 9 Brown and Sharpe gauge in a relatively low-speed telegraph circuit, for correction of 25-cycle interference.

The neutralizing transformer may be used for simultaneous correction of several frequencies. An arrangement in service for removing 25- and 75-cycle interference is shown in figure 4, and includes, in addition to the transformer, a second capacitor and an added reactor.

The above transformers were designed for use during normal working of the disturbing power or railway system. A unique application has been made in a five-mile exposure of an electrified railway to circuits of a burglar-alarm system, where frequent railway short circuits caused false alarms by induction. In this case the induction reached values over 100 volts which were interrupted in about one cycle through the operation of railway circuit breakers. A transformer was provided which could adjust itself sufficiently quickly to correct the transient voltage, by tuning to 25 and 50 cycles through the use of two coil-capacitor units shunting the primary coil, and was effective in neutralizing the abrupt severe surges of voltage.

### Neutralizing Generator

The neutralizing generator formerly has been in service use but is now superseded by the system next to be described. It will be discussed briefly because of the light it throws on the general problem.

Various arrangements of this have been developed, of which one is shown in figure 5. A multiwire transformer is energized by means of an a-c generator, and counterbalances the induced voltages both in telegraph wires and in the pilot wire. Any residual voltage in the latter is rectified in a mechanical rectifier driven synchronously with the generator, and after amplification serves to correct the voltage of the generator and the speed of the driving motor until the correct compensation is effected.

The system is effective in correcting interference, but is sluggish in adjusting itself when changes occur in the induced voltage. All a-c components of the telegraph signals must flow through the generator armature, and in order to minimize the addition of impedance in the telegraph wires and the tendency to cause cross fire between them, the impedance of the armature must be held to a low value. The pilot wire may be of the wire size ordinarily used for telegraphy, and the system is practical for exposures much longer than is the multiwire neutralizing system previously described.

### Neutralizing Amplifying System

This system is probably the most valuable of those available. It has made it possible to maintain practically normal operation in over 260 telegraph wires which are exposed to interference at 25 cycles from the electrified zone of a large eastern railroad, where voltages approaching 200 volts are induced. The system is also in use elsewhere for correcting interference at 60 cycles.

The neutralizing amplifying system is illustrated in figures 6 and 7. As with systems previously described, a transformer serves to impress on each telegraph wire a voltage to counteract the disturbing voltage induced in line wires. In this case the transformer is energized by a vacuum-tube amplifier. The voltage induced in the pilot wire is also opposed by the voltage in one coil of the transformer, and the residual is impressed upon the amplifier. The ratio of the potentiometer is not the same as the turns ratio of the opposing coil with respect to the line coils. Through adjustment of each of these ratios it is possible to obtain a step-up action which provides neutralization approaching 97 per cent. Since the system is aperiodic, it is able to neutralize sudden surges of voltage such as caused by power-system short circuits, as well as continuous interference within the voltage limitations of the equipment.

The manner of providing for the passage of the useful telegraph currents is unique. It might appear that the arrangement would impress a high impedance upon the telegraph currents, and would tend to add cross fire between circuits. The circuit, however, is such that a current is caused to flow in the transformer coil in the output of the amplifier, which (corrected for turns ratio) is equal to the sum of the telegraph currents in all line coils, thus cancelling any flux in the transformer due to telegraph currents. If the current in the output coil departs from the amount to

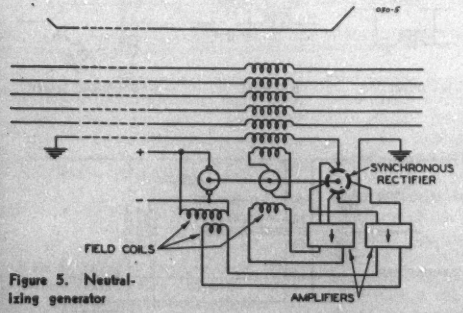


Figure 5. Neutralizing generator

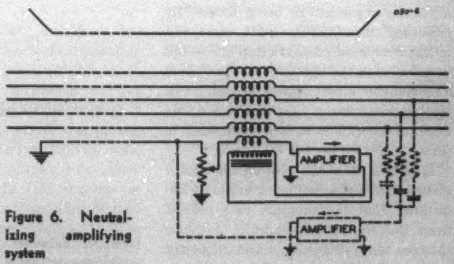


Figure 6. Neutralizing amplifying system

**Figure 7. Neutralizing amplifying system for correction of 150 volts at 25 cycles in 60 telegraph wires**

balance the telegraph currents, a residual voltage is immediately impressed upon the input of the amplifier tending to correct that condition.

A complication occurs in connection with the cross fire which normally occurs between telegraph wires carried on a given pole line. If the cross fire between all circuits including the pilot wire were equal, this system would also be effective in reducing the cross fire. Actually it is impracticable to locate the pilot wire in a manner to prevent its being affected by enhanced cross fire from a few wires, and unless compensated that cross fire would interfere with the operation of the system as a whole. Where high-speed telegraph circuits are present a correction for this crossfire condition is necessary and is shown in dotted lines in the figure.

With one set of the neutralizing equipment as shown, a limitation exists in the distance that the exposure may extend from the equipment, because of phase changes along the wire. The efficiency tends to decrease where the distance exceeds 20 miles in the case of 60-cycle interference, or where it exceeds 40 miles with 25-cycle interference. These distances are reduced if the telegraph wires are in cable. These limitations are removed by utilizing two sets of equipment, one at or beyond each end of the exposure, in which case the pilot wire may be 200 miles or more in length.

An arrangement somewhat similar in principle to the one illustrated was first shown by H. M. Trueblood of the Bell Telephone Laboratories. In its present form the system was developed here by W. D. Cannon.

## Mitigative Systems Dependent Upon Tuning

Many combinations of reactors and capacitors have been proposed with the view to reducing or removing extraneous sinusoidal currents by tuning. The expense of a pilot wire is thus avoided. The tuning removes those same frequencies from the useful telegraph currents and thus may impair the operation of the telegraph circuit by an amount dependent upon the relative frequency of the telegraph and the interfering frequencies, and upon the breadth of the tuning. A description of a small number of tuned devices will suffice to illustrate their practical value in mitigating interference.

### Resonant Shunts and Resonant Chokes

A simple resonant shunt or choke, as shown in figures 8*A* and 8*B*, was introduced early for removal of interference. It may remove 95 per cent of the interference, but because of its coincident removal of useful telegraph currents it can be used only where the dot telegraph frequency is less than about half of the interfering frequency. This greatly restricts its use in modern systems of telegraphy. The effectiveness of the coil increases with its size; the above statements are based upon the use of an inductor weighing 20 pounds.

While simple resonant devices cannot be used for removal of 25- or 60-cycle interference from high-speed telegraph circuits, the resonant shunts are effective in such circuits where the interference results from power harmonics at 180 cycles. For application where conditions permit, the resonant shunt is placed in parallel with the working telegraph relay. The resonant choke is convenient for use in "way" telegraph circuits where a number of stations operate on the same line, since one choke may serve where several of the resonant shunts would be required.

### Balanced Double-Resonant Network

A balanced arrangement shown in figure 8*C* was proposed by E. Blakeney and R. E. Chetwood, which in theory may remove all of the interference. The resistor is adjusted to equal the a-c resistance of the coil and capacitor at resonance. Advantage may be taken of the arrangement to increase the value of the inductance and reduce the amount of capacitance, with the result that the impairment to the telegraph is much reduced.

That arrangement has been little used, but a development from the same principle is the balanced double-resonant network shown in figure 9. The theory of this is rather involved, but it may be considered that the a-c resistance of a double-resonant shunt is balanced against that of the resonant choke combination in a manner to remove nearly all interference. Partly through the circuit design and

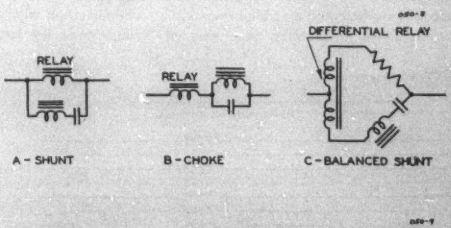


**Figure 8. Resonant devices for reducing interference**

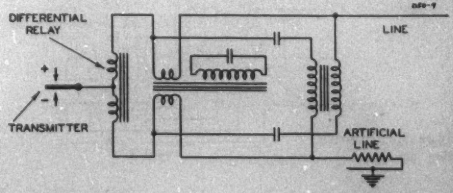


**Figure 9. Balanced double-resonant network**

partly through an increase in the weight and effectiveness of the inductors, a much improved performance results. Each inductor is designed to offer the highest ratio of reactance-to-resistance obtainable within practicable size limits. The cores are of silicon steel and contain air gaps. This device is wholly practical, and with some moderate impairment of the telegraph currents it may be used where the telegraph dot frequency approaches nine-tenths of the interfering power frequency. Typical plots showing the efficiencies of various tuned devices in removing interference are shown in figure 10.

The effectiveness of the balanced double-resonant network is dependent upon the power frequency remaining nearly constant. Failures of the device in removing interference have occurred because of variations in the frequency of the disturbing power system.

### Synchronous Selective Neutralizing System

The arrangement just described provides nearly the practical limit of sharpness of tuning which may be secured with direct use of coil-capacitor tuning. It is possible to obtain selectivity many times closer through the use of mechanical tuning, or by an arrangement which involves rectification, a delay network, and reconversion to alternating current. A system of this type is indicated in figure 11. With such tuning as plotted in figure 10, the amount removed from the telegraph frequency spectrum is so narrow, presuming that random telegraph traffic is transmitted, that the impairment to the telegraph signals is not serious, and the telegraph dot frequency is not limited to values below the disturbing frequency as was the case with other tuned devices.

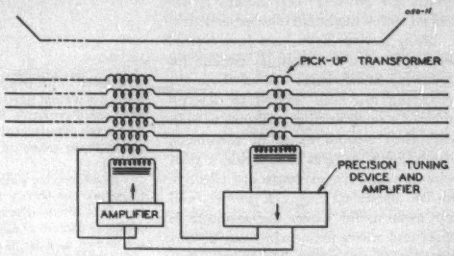


**Figure 11. Synchronous selective neutralizing system**

In practice a complication occurs because the telegraph signals are not wholly random. Certain characters, for example the letter "e", the space between words, etc., occur more frequently than others. When one multiplex channel is idle a blank is transmitted repeatedly, and at times circuit testing is done with a recurring set of characters. When telegraph signals containing such combinations are analyzed into their sinusoidal components (see section on telegraph theory) it is found that certain frequencies are more prominent than others and if one of those frequencies should nearly coincide with the interfering frequency there is impairment of signals and possible cross fire between circuits.

The values of those prominent frequencies have been computed by setting up combinations of signals likely to occur. For a two-channel multiplex it is found that the prominent frequencies are given by the formula $nF/5$, where $F$ is the dot telegraph frequency and $n$ takes all integer values from one to infinity. For the three-channel multiplex the formula is $2nF/15$, and in the four-channel multiplex it is $nF/10$. An exception is that frequencies of $2F$, $4F$, $6F$, etc., are not present, and frequencies near those values are of little importance.

There are, therefore, limitations upon the telegraph circuit speeds which can be worked to best advantage on a line where a synchronous selective neutralizing system is in use. A list of the telegraph dot frequencies to be avoided under these circumstances, as determined from the above formulas, where the interference is at 60 cycles, appears in table I.

Provision for passage of the useful telegraph currents is made in the same manner as in the neutralizing amplifying system previously described. The system is of course quite complex, and has the further disadvantage that a time interval of the order of 20 seconds is required for it to readjust itself for changes in amount of induced voltage, this sluggishness being a corollary of the extraordinarily sharp tuning. During that interval the interference remains partly uncorrected. Arrangements are incorporated for automatic adjustment of the frequency of the tuning to follow normal changes in the frequency of the power system. Interference from two unsynchronized power systems cannot be neutralized by a single set of this equipment.

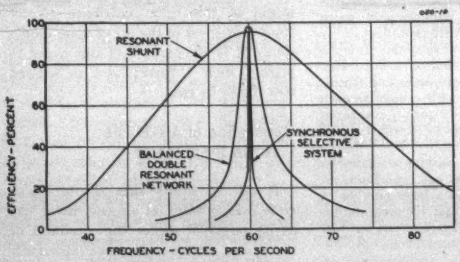


**Figure 10. Efficiency of removal of sinusoidal currents by tuned devices**

**Table I. Telegraph Dot Frequencies Which Conflict With Operation of 60-Cycle Synchronous Selective Neutralizing System**

| | | | | |
|---|---|---|---|---|
| Two-channel multiplex | 25.0 | 27.3 | 33.2 |
| | 37.5 | | |
| Three-channel multiplex | 37.5 | 40.9 | 45.0 |
| | 50.0 | 56.2 | |
| Four-channel multiplex | 50.0 | 54.6 | 60.0 |
| | 66.7 | 75.0 | |

The values listed include only those which occur within the customary range of operation of the stated equipment.

## Discussion and Conclusions

This discussion of methods for mitigating interference obviously has been quite one-sided, since due to limitations of space there has been no discussion of matters of design of the power system which may influence the interference, yet in many cases the best solution will call

for some modification of the plans of the latter. Such matters are dealt with in various other publications. In general those features should receive consideration with every exposure, since the only procedure that can be justified is that in which the greatest total benefit is obtained with a minimum total expenditure.

Many devices have been investigated for application to telegraph circuits for removing interference, and of those the preceding has been limited to descriptions of a small number sufficient to indicate their general range of usefulness. Neutralizing systems embodying a pilot wire through the exposure are effective for all classes of telegraph service, and are most useful where the exposure is short and where many wires can be corrected with one set of equipment. Systems dependent upon tuning are frequently unsuitable because of a greater tendency to cause direct detrimental effects to the telegraph currents, but find application in some circumstances where pilot-wire methods would be uneconomical.

But because of the cost, of the added complexity in telegraph circuits already highly complex, and of the weakening of the useful signaling currents in some cases, there are often objections to the use of such correcting equipment in exposures causing moderate or small amounts of power induction. In each instance there is some minimum value of induced voltage below which the application of neutralizing devices is not justifiable. To the telegraph company the most serious type of exposure is that which creates small interference only—a conclusion which follows from the fact that such exposures are far more numerous than the more severe ones, and their damaging effect upon telegraph service is to some extent additive.

However, the application of neutralizing devices to the telegraph circuits is proper where conditions are such that the creation of an exposure causing material induced voltages is justifiable, and fortunately it is possible to state that through the use of different methods in different cases there have been few exposures which during normal conditions of the power system, are so severe individually as to effect any serious impairment to telegraph service.

## Discussion

Discussion will be found in the 1940 annual TRANSACTIONS volume and in the 1940 "Transactions Supplement" to ELECTRICAL ENGINEERING.

# Harmonic Theory of Noise in Induction Motors

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**Synopsis:** This paper presents a theory of noise generation particularly adapted to use with small motors. Since single-phase motors predominate in the small-motor field, a single-phase point of view has been employed.

The underlying philosophy of the paper is to reduce the theory to simplest terms and to concentrate attention upon the most probable sources of noise. While the results are shown as a large collection of numbers representing force waves the development steps of the theory are really simple and easily understood.

The resultant air-gap flux wave in an induction motor is the difference between the fundamental stator flux plus its harmonics and the fundamental rotor flux plus its harmonics. The difference between the two fundamental fluxes is usually less than the larger one and often less than either one but the harmonics, with few exceptions, are neither of the same velocity nor space order and, therefore, do not add or subtract from each other. It follows that the resultant flux wave has more harmonics of much greater per-unit amplitude than does either the stator or rotor flux wave alone. It is the interaction of two large harmonic flux waves of slightly different space order and traveling at high frequency with respect to each other that causes high-frequency magnetic-force waves of long space pitch which are effective in producing noise.

The theory has been used for some time in noise investigations and has been found to bear out test results on a large number of motors. It is hoped that its presentation will not only prove useful to others but will encourage further contributions to the understanding of noise.

THE present-day problems which confront the designers of electric motors have been to a considerable extent complicated by the necessity for producing motors of greater and greater quietness. Since the pressure of economics precludes the possibility of obtaining quietness by the introduction of massive structures, ways must be found to obtain desired levels of quietness with the same or lighter structures than those previously used.

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There have been a number of papers on noise of electrical machinery which have undertaken to deal with the problem of producing quiet motors from a scientific designer point of view. Many of these papers have been unsatisfactory to those engineers who desire always to have a sound and rigorous theory against which to check data, form conclusions, and make predictions. Much of the work which has been presented on noise has been of an experimental nature and has been presented at least semiempirically. Other work has been presented which, experience indicates, appears to be based upon unnecessarily complicated conceptions.

It appears that a sound theory having a simple philosophy and starting from a few simple fundamental assumptions would at this time contribute greatly toward progress in the art of noise reduction. It is the purpose of this paper to present such a theory and to suggest how it may be used.

## Generation of Air-Borne Noise By a Motor

It can be shown that the air-borne noise arising from an electric motor has as its principal source the vibration of the stator frame and yoke structure. The natural and correct assumption is that the magnetic forces set up in the air gap of the motor cause the frame structure to be distorted periodically with time and that the external surface of the frame in turn beats the air causing air-borne noise.

From the above conception of the mechanism of noise production it follows that a complete exposition of motor noise phenomena would include not only a method for determining the character, magnitude, and frequency of the disturbing forces set up in the air gap but also a means for determining the response of the stator structure to the disturbing forces.

Unfortunately, experience with tests on many motors indicates that there is sufficient variation in the response characteristics of apparently identical stator structures (assembled in complete motor)

**Chart I. List of Largest Noise Force Waves**

| Stator Harmonic | Rotor Harmonic | Noise Frequency | Length of Magnetic Force Pole |
|---|---|---|---|
| $N_f$ or $M_f$ | $R_f$ | $f[R(1-s)-1-s]$ | $\frac{\lambda}{R-N}$ or $\frac{\lambda}{R-M}$ |
| $N_f$ or $M_f$ | $R_b$ | $f[R(1-s)+1-s]$ | $\frac{\lambda}{R-N}$ or $\frac{\lambda}{R-M}$ |
| $N_f$ or $M_f$ | $T_f$ | $f[T(1-s)-1+s]$ | $\frac{\lambda}{T-N}$ or $\frac{\lambda}{T-M}$ |
| $N_f$ or $M_f$ | $T_b$ | $f[T(1-s)-3+s]$ | $\frac{\lambda}{T-N}$ or $\frac{\lambda}{T-M}$ |
| $N_b$ or $M_b$ | $R_f$ | $f[R(1-s)+1-s]$ | $\frac{\lambda}{R-N}$ or $\frac{\lambda}{R-M}$ |
| $N_b$ or $M_b$ | $R_b$ | $f[R(1-s)+3-s]$ | $\frac{\lambda}{R-N}$ or $\frac{\lambda}{R-M}$ |
| $N_b$ or $M_b$ | $T_f$ | $f[T(1-s)+1+s]$ | $\frac{\lambda}{T-N}$ or $\frac{\lambda}{T-M}$ |
| $N_b$ or $M_b$ | $T_b$ | $f[T(1-s)-1+s]$ | $\frac{\lambda}{T-N}$ or $\frac{\lambda}{T-M}$ |

to leave little hope that in the near future a reasonably exact expression for stator response can be presented. Calculations of stator response do have their place in a noise investigation but the results obtained thus far have been more qualitative than quantitative.

Because of the, as yet, unsatisfying results which have come from efforts to predetermine frame response characteristics no effort is being made in this paper to discuss this point. It is felt better to confine our attention to the subject of the magnetic forces causing noise and leave for the future the subject of the accurate calculation of the stator response. By presenting now that which is known for certain, effort on the part of others may be stimulated which will result in further advances in the art.

The theory will be based upon the assumption of an air gap having uniform length, constant permeance, and windings which are distributed in the usual way in finite numbers of slots. Such assumptions can be well justified in small electrical machinery where substantially closed slots are employed and where the problem of noise reaches its most acute form. In larger motors having open slots it is felt that many of the conclusions obtained by this theory will still be valuable because accompanying the use of open slots is the use of greatly increased air gaps which to a considerable extent minimize such phenomena as may arise from effects due exclusively to permeance variations. Another reason why the conclusions arrived at from this magnetomotive-force constant-permeance theory may be useful where the permeance is not really constant lies in the fact that analysis has shown that most of the phenomena arising from tooth and slot permeance variations are identical in every way with associated phenomena arising from harmonics of magnetomotive-force caused by windings placed in the same slot structure.

## Development of Theory

It is well known that, in addition to the fundamental air-gap fluxes produced by the currents in the rotor and stator windings, harmonic fluxes are also produced. With symmetrical windings harmonic fluxes, with certain exceptions, may exist having a number of poles corresponding to any odd multiple of the fundamental number of poles. "Good" winding distributions generally limit the magnitude of harmonics of low order but with a given number of uniformly spaced slots nothing can be done about the magnitudes of the tooth harmonics because the "distribution factor" for the tooth harmonics is identical with that for the fundamental flux. With any given slot combination and fundamental number of poles the magnitudes and orders of the tooth harmonics are definitely determined in relation to the fundamental flux. There always exist an infinite series of tooth harmonics having magnitudes and orders as shown below.

$$\text{Order of harmonic} = \frac{\text{harmonic poles}}{\text{fundamental poles}} = 2Kn \pm 1 \quad (1)$$

$$\text{Amplitude of harmonic wave} = A_1 \frac{1}{2Kn \pm 1} \quad (2)$$

In the above equations

$P_1$ = fundamental number of poles
$A_1$ = amplitude of fundamental flux wave
$n$ = number of teeth per pole
$K$ = any integer

It will be noticed that the tooth harmonics go in pairs and that if there are nine teeth per pole in a 4-pole motor the largest pair of tooth harmonics are the 17th and 19th harmonics. These harmonics will have respectively 17 and 19 times as many poles as the fundamental flux and their amplitudes will be $^1/_{17}$ and $^1/_{19}$ that of the fundamental. The next largest harmonics will be the 35th and 37th and after these the 53d and 55th, etc.

There may be times when the second or third largest tooth harmonics will be important in producing noise but for the present only the largest tooth harmonics will be considered. The method outlined can be employed for any number of harmonics.

For the sake of clarity and to give a mental picture of the relative magnitudes involved, figure 1 has been prepared showing (dotted) the stair-step wave of flux produced by a four-pole winding in a 36-slot stator. Superposed is shown (solid) the fundamental component and the first pair of tooth harmonics corresponding to the stair-step wave. Both the harmonics as well as the fundamental wave of flux should be visualized as pulsating with time and, if it be assumed that figure 1 was drawn when the waves were maximum, the effect of the pulsation is exactly duplicated by dividing each pulsating wave into two oppositely gliding components each having half the amplitude shown.

If the forward and backward components be used there are now six stator flux waves to be considered. If the subscript "1" be always associated with the stator and the subscripts "$N$" and "$M$" are each associated with a member of and represent the order of the first pair of tooth harmonics, the forward and backward components of each wave may be expressed as shown below.

$$\left.\begin{aligned}
W_{1f} &= A_{1f}\cos\left[x\frac{\pi}{\lambda} - \omega t\right] \\
W_{1b} &= A_{1b}\cos\left[x\frac{\pi}{\lambda} + \omega t\right] \\
W_{1Nf} &= A_{Nf}\cos\left[Nx\frac{\pi}{\lambda} - \omega t\right] \\
W_{1Nb} &= A_{Nb}\cos\left[Nx\frac{\pi}{\lambda} + \omega t\right] \\
W_{1Mf} &= A_{Mf}\cos\left[Mx\frac{\pi}{\lambda} - \omega t\right] \\
W_{1Mb} &= A_{Mb}\cos\left[Mx\frac{\pi}{\lambda} + \omega t\right]
\end{aligned}\right\} \quad (3)$$

The forward component of fundamental stator flux acts on the rotor winding to produce a forward wave of rotor currents which in turn produces a forward wave of rotor fundamental flux moving at slip frequency with respect to the rotor. Associated with this forward fundamental

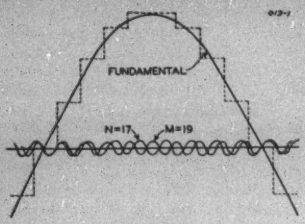



**Figure 1. Fundamental and first tooth harmonics**

flux is an infinite series of rotor tooth harmonic fluxes. Unlike the stator fluxes, the rotor fluxes, arising as they do from the action of a gliding wave of stator flux having constant magnitude, are not pulsating. They glide forward and backward on the rotor (forward with respect to the stator) with constant magnitude and at slip frequency with respect to the rotor.

The rotor tooth harmonics have poles and amplitudes as shown below:

$$\text{Order of rotor harmonic} = \frac{\text{harmonic poles}}{\text{fundamental poles}} = \pm\frac{2KB}{P_1}+1 \quad (4)$$

$$\text{Amplitude of rotor harmonics} = A_{Nf}\left(\frac{1}{\pm\frac{2KB}{P_1}+1}\right) \quad (5)$$

In the above equations:

$P_1$ = fundamental number of poles
$A_{Nf}$ = amplitude of forward fundamental rotor wave
$B$ = total number of rotor bars
$K$ = any integer

When $K=0$ in equation 4, the first harmonic (the fundamental flux) is obtained and the positive sign indicates that the direction of motion of the fundamental flux wave with respect to the rotor is considered positive. A negative sign such as always occurs with the lesser-poled harmonic of each pair of tooth harmonics indicates that that harmonic is moving around the rotor in a direction opposite the motion of the fundamental flux. Throughout this discussion $R$ indicates the negatively moving rotor tooth harmonic and the ratio of its poles to the poles of the fundamental. $T$ will indicate the positively moving rotor harmonic and the ratio of its poles to those of the fundamental.

The backward component of fundamental stator flux is also responsible for producing a backward component of fundamental rotor flux gliding backward on the rotor at a frequency $(2-s)$ times the stator frequency. Corresponding tooth harmonics are also produced.

If only the fundamental and first pair of tooth harmonics be considered at this time there are in all six rotor fluxes. Neglecting the difference in time phase between stator and rotor currents, these six fluxes may be expressed with respect to the rotor as shown.

$$\left.\begin{aligned}
W_{1f} &= A_{1f}\cos\left[x_1\tfrac{\pi}{\lambda}-\omega st\right]\\
W_{1b} &= A_{1b}\cos\left[x_1\tfrac{\pi}{\lambda}+\omega(2-s)t\right]\\
W_{1Rf} &= A_{Rf}\cos\left[Rx_1\tfrac{\pi}{\lambda}+\omega st\right]\\
W_{1Tf} &= A_{Tf}\cos\left[Tx_1\tfrac{\pi}{\lambda}-\omega st\right]\\
W_{1Rb} &= A_{Rb}\cos\left[Rx_1\tfrac{\pi}{\lambda}-\omega(2-s)t\right]\\
W_{1Tb} &= A_{Tb}\cos\left[Tx_1\tfrac{\pi}{\lambda}+\omega(2-s)t\right]
\end{aligned}\right\} \quad (6)$$

With respect to the stator the rotor waves of (6) can be written:

$$\left.\begin{aligned}
W_{1f} &= A_{1f}\cos\left[x\tfrac{\pi}{\lambda}-\omega t\right]\\
W_{1b} &= A_{1b}\cos\left[x\tfrac{\pi}{\lambda}+\omega t\right]\\
W_{1Rf} &= A_{Rf}\cos\left[Rx\tfrac{\pi}{\lambda}-\omega[R(1-s)-s]t\right]\\
W_{1Tf} &= A_{Tf}\cos\left[Tx\tfrac{\pi}{\lambda}-\omega[T(1-s)+s]t\right]\\
W_{1Rb} &= A_{Rb}\cos\left[Rx\tfrac{\pi}{\lambda}-\omega[R(1-s)+2-s]t\right]\\
W_{1Tb} &= A_{Tb}\cos\left[Tx\tfrac{\pi}{\lambda}-\omega[T(1-s)-2+s]t\right]
\end{aligned}\right\} \quad (7)$$

The flux at every point in the air gap of the motor and at every instant of time is exactly representable as the sum of the fundamental fluxes and all the harmonic fluxes. Using those which have been considered we may write:

$$B_\delta = \left[\begin{aligned}&W_{1f}+W_{1b}+W_{1Nf}+W_{1Nb}+W_{1Mf}+\\&W_{1Mb}+W_{1f}+W_{2b}+W_{2Rf}+W_{2Rb}+\\&W_{1Tf}+W_{1Tb}\end{aligned}\right] \quad (8)$$

The radial force density at any point in the gap due to $B_\delta$ is, according to Maxwell:

$$\frac{F}{A}=\frac{1}{72{,}130{,}000}B_\delta^2 \text{ pounds per square inch} \quad (9)$$

For purposes of noise study it is desirable to work with the components of the force density, which components are obtainable by the expansion of the square of the right member of (8). The expansion consists of the square of each term in (8) plus twice the product of each term with each other term. A complete expansion of even so few as the 12 terms chosen leads to 78 terms which are rather clumsy to handle by conventional means. In the appendix is given a simple shorthand means for performing the expansion and there has been prepared a multiplication table showing results for the case of a four-pole 36–48 combination motor.

At this time it is of interest to perform one of the multiplications in order to discuss the results obtained. In the case of the $N$ forward stator tooth harmonic and the $R$ forward rotor harmonic the product is:

$$\Delta F_{(Nf)(Rf)} = A_{Nf}A_{Rf}\cos\left[Nx\tfrac{\pi}{\lambda}-\omega t\right]\times\cos\left[Rx\tfrac{\pi}{\lambda}-\omega[R(1-s)-s]t\right] \quad (10)$$

$$\Delta F_{(Nf)(Rf)} = A_{Nf}A_{Rf}\times\left\{\cos\left[(R-N)x\tfrac{\pi}{\lambda}-\omega[R(1-s)-1-s]t\right]+\cos\left[(R+N)x\tfrac{\pi}{\lambda}-\omega[R(1-s)+1-s]t\right]\right\} \quad (11)$$

It will be seen from (11) that the product of the two flux waves is representable as two force waves, the upper wave having a long wave length and the lower one having a very short wave length.

**Chart II. No-Load Noise Forces for Four-Pole 36–48 Motor**

| Stator Harmonic | Rotor Harmonic | Frequency (Cycles) | Amplitude (Pounds Per Square Inch) | Length of Magnetic Force Pole (Inches) |
|---|---|---|---|---|
| $17_f$ | $23_b$ | 1,440 | 0.032 | 0.46 |
| $19_f$ | $23_b$ | 1,440 | 0.0286 | 0.685 |
| $17_b$ | $23_b$ | 1,560 | 0.032 | 0.46 |
| $19_b$ | $23_b$ | 1,560 | 0.0286 | 0.685 |
| $17_f$ | $25_b$ | 1,320 | 0.0294 | 0.46 |
| $19_f$ | $25_b$ | 1,320 | 0.0264 | 0.685 |
| $17_b$ | $25_b$ | 1,440 | 0.0294 | 0.46 |
| $19_b$ | $25_b$ | 1,440 | 0.0264 | 0.685 |

Chart III. Magnetic Force Waves for 36–48 Combination

| | | STATOR HARMONICS | | | | | | | | | | ROTOR HARMONICS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 +1 | | 1 −1 | | 17 +1 | | 17 −1 | | 19 +1 | 19 −1 | 23 +2.5 | | 23 +2.5 | | 25 +2.5 | | 25 +2.5 | | | |
| STATOR HARMONICS | 1 | 2 | 0 | 2 | 0 | 18 | 16 | 18 | 16 | 20 | 18 | 20 | 18 | 24 | 22 | 24 | 22 | 26 | 24 | 26 | 24 |
| | +1 | 2 | 0 | 0 | 2 | 2 | 0 | 0 | 2 | 2 | 0 | 0 | 2 | 26 | 24 | 24 | 22 | 24 | 22 | 26 | 24 |
| | 1 | 2 | 0 | 2 | 0 | 18 | 16 | 18 | 16 | 20 | 18 | 20 | 18 | 24 | 22 | 24 | 22 | 26 | 24 | 26 | 24 |
| | −1 | 0 | 2 | 2 | 0 | 2 | 2 | 0 | 0 | 2 | 2 | 0 | | 24 | 26 | 22 | 24 | 22 | 26 | 24 | 26 |
| | 17 | 18 | 16 | 18 | 16 | 34 | 0 | 34 | 0 | 36 | 2 | 36 | 2 | 40 | 6 | 40 | 6 | 42 | 8 | 42 | 8 |
| | +1 | 2 | 0 | 0 | 2 | 2 | 0 | 0 | 2 | 2 | 0 | 0 | 2 | 26 | 24 | 24 | 22 | 24 | 22 | 26 | 24 |
| | 17 | 18 | 16 | 18 | 16 | 34 | 0 | 34 | 0 | 36 | 2 | 36 | 2 | 40 | 6 | 40 | 6 | 42 | 8 | 42 | 8 |
| | −1 | 0 | 2 | 2 | 0 | 2 | 2 | 0 | 0 | 2 | 2 | 0 | | 24 | 26 | 22 | 24 | 22 | 26 | 24 | 26 |
| | 19 | 20 | 18 | 20 | 18 | 36 | 2 | 36 | 2 | 38 | 0 | 38 | 0 | 42 | 4 | 42 | 4 | 44 | 6 | 44 | 6 |
| | +1 | 2 | 0 | 0 | 2 | 2 | 0 | 0 | 2 | 2 | 0 | 0 | 2 | 26 | 24 | 24 | 22 | 24 | 22 | 26 | 24 |
| | 19 | 20 | 18 | 20 | 18 | 36 | 2 | 36 | 2 | 38 | 0 | 38 | 0 | 42 | 4 | 42 | 4 | 44 | 6 | 44 | 6 |
| | −1 | 2 | 0 | 0 | 2 | 2 | 0 | 0 | 2 | 2 | 0 | 0 | 2 | 24 | 26 | 22 | 24 | 22 | 24 | 24 | 26 |
| ROTOR HARMONICS | 23 | 24 | 22 | 24 | 22 | 40 | 6 | 40 | 6 | 42 | 4 | 42 | 4 | 46 | 0 | 46 | 0 | 48 | 2 | 48 | 2 |
| | +2.5 | 26 | 24 | 24 | 26 | 26 | 24 | 24 | 26 | 26 | 24 | 24 | 26 | 50 | 0 | 48 | 2 | 48 | 2 | 50 | 0 |
| | 23 | 24 | 22 | 24 | 22 | 40 | 6 | 40 | 6 | 42 | 4 | 42 | 4 | 46 | 0 | 46 | 0 | 48 | 2 | 48 | 2 |
| | +2.3 | 24 | 22 | 22 | 24 | 24 | 22 | 22 | 24 | 24 | 22 | 22 | 24 | 48 | 2 | 46 | 0 | 46 | 0 | 48 | 2 |
| | 25 | 26 | 24 | 26 | 24 | 42 | 8 | 42 | 8 | 44 | 6 | 44 | 6 | 48 | 2 | 48 | 2 | 50 | 0 | 50 | 0 |
| | +2.3 | 24 | 22 | 22 | 26 | 24 | 22 | 22 | 24 | 24 | 22 | 22 | 24 | 48 | 2 | 46 | 0 | 46 | 0 | 48 | 2 |
| | 25 | 26 | 24 | 26 | 24 | 42 | 8 | 42 | 8 | 44 | 6 | 44 | 6 | 48 | 2 | 48 | 2 | 50 | 0 | 50 | 0 |
| | +2.5 | 26 | 24 | 24 | 26 | 26 | 24 | 24 | 26 | 26 | 24 | 24 | 26 | 50 | 0 | 48 | 2 | 48 | 2 | 50 | 0 |
| | 1 | 2 | 0 | 2 | 0 | 18 | 16 | 18 | 16 | 20 | 18 | 20 | 18 | 24 | 22 | 24 | 22 | 26 | 24 | 26 | 24 |
| | +1 | 2 | 0 | 0 | 2 | 2 | 0 | 0 | 2 | 2 | 0 | 0 | 2 | 26 | 24 | 24 | 22 | 24 | 22 | 26 | 24 |
| | 1 | 2 | 0 | 2 | 0 | 18 | 16 | 18 | 16 | 20 | 18 | 20 | 18 | 24 | 22 | 24 | 22 | 26 | 24 | 26 | 24 |
| | −1 | 0 | 2 | 2 | 0 | 2 | 2 | 0 | 0 | 2 | 2 | 0 | | 24 | 26 | 22 | 24 | 22 | 26 | 24 | 26 |

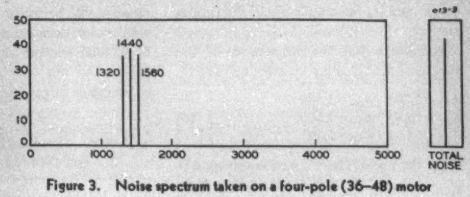



Figure 3. Noise spectrum taken on a four-pole (36–48) motor

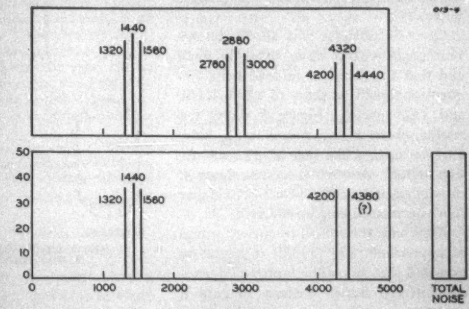



Figure 4

Top—Calculated noise-force spectrum on a four-pole (36–48) motor
Bottom—Noise spectrum taken on a four-pole (36–48) motor

In general, very short force waves will not be important because the stator will be very stiff to short-wave distortion. Long waves of force, however, will cause a relatively large response and therefore

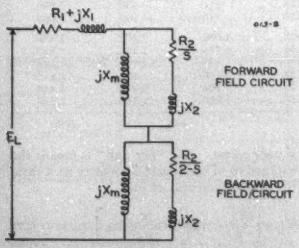



Figure 2. Equivalent circuit for a single-phase motor

will be important in producing noise. The pitch of the long force wave is:

$$\lambda_{(N/)(R/)} = \frac{\lambda}{R-N} \tag{12}$$

The frequency of this wave is:

$$f_{(N/)(R/)} = f[R(1-s)-1-s] \tag{13}$$

and this frequency is, of course, the frequency at which the air-borne noise will be emitted.

A study of the various products involved shows that those products most likely to be responsible for noise are the ones of long pitch produced by the multiplication of a stator harmonic with a rotor harmonic. There are 16 such products and they will be listed here for future reference (chart I). In appendix I a complete listing of the product terms is given but the simplifying assumption has been made that $s=0$. It may at times be desirable to have available the expression for noise frequency when $s \neq 0$.

It will be noted that the frequency does not change when the $N_f$ stator harmonic is substituted for the $M_f$ but the force wave length does.

## Sample Force-Wave Calculation

A specific calculation will now be introduced to show how the force waves may be calculated for a particular motor.

ASSUMPTIONS

| | |
|---|---|
| Gap diameter | =3.5 inches |
| Stacking length | =2 inches |
| Stator slots | =36 |
| Rotor slots | =48 |
| Fundamental poles | =4 |
| Maximum fundamental density | =30,000 lines per square inch |
| Maximum load current | =2 (no load current) |

The order of the largest stator tooth harmonics may be calculated by means of equation 1.

$$\left.\begin{aligned} N &= 17 \\ M &= 19 \end{aligned}\right\} \tag{14}$$

The order of the largest rotor tooth harmonics may be calculated by means of (4).

$$\left.\begin{aligned} R &= 23 \\ T &= 25 \end{aligned}\right\} \tag{15}$$

At no load the forward field rotor currents are negligible (see figure 2) and the forward-field rotor tooth harmonics listed on chart I will be ineffective in producing noise. In the backward field, while the rotor and stator fundamental fluxes neutralize each other, as shown by the low voltage which exists across the backward field at no load, it will be assumed that because of poor distribution factor and spiral the harmonics exist practically undiminished.* On the basis of this assumption the stator harmonic fluxes and the backward-field rotor harmonic fluxes are subject to the same ampere turns as is the fundamental flux; consequently they will exist in their normal magnitudes $(A_1/h)$ where $h$ is the order of the har-

* NOTE: If desired the rotor secondary characteristics to each stator harmonic can be carefully calculated and an exact determination of the diminution of the stator harmonic fluxes determined. The stator winding will have almost no diminishing effect on rotor harmonics.

monic and $A_1$ the amplitude of the fundamental. [See (2) and (5).]

It follows that the amplitudes of the harmonics in lines per square inch are:

$$\left.\begin{aligned} A_{17f} &= 1{,}765 \quad A_{19b} = 1{,}580 \\ A_{19f} &= 1{,}580 \quad A_{21b} = 1{,}305 \\ A_{17b} &= 1{,}765 \quad A_{21b} = 1{,}200 \end{aligned}\right\} \quad (16)$$

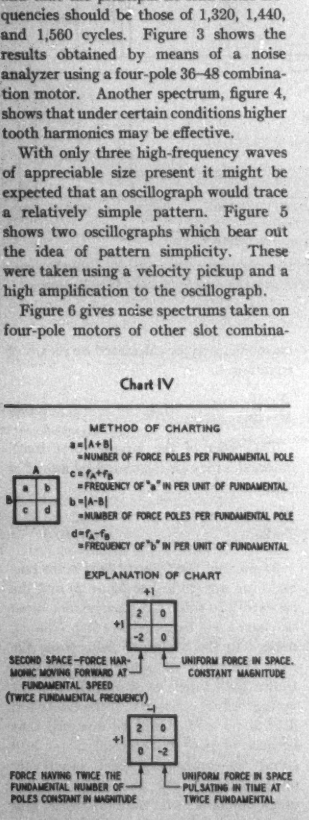
By the use of chart I and equation 9 it is now possible to list maximum force densities, frequencies, and wave lengths (chart II).

Chart II indicates that all the important magnetic-force waves should be small and that the principal no-load noise frequencies should be those of 1,320, 1,440, and 1,560 cycles. Figure 3 shows the results obtained by means of a noise analyzer using a four-pole 36–48 combination motor. Another spectrum, figure 4, shows that under certain conditions higher tooth harmonics may be effective.

With only three high-frequency waves of appreciable size present it might be expected that an oscillograph would trace a relatively simple pattern. Figure 5 shows two oscillographs which bear out the idea of pattern simplicity. These were taken using a velocity pickup and a high amplification to the oscillograph.

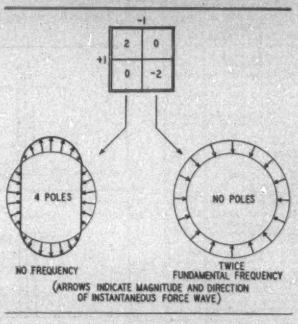
Figure 6 gives noise spectrums taken on four-pole motors of other slot combinations. These may be compared with chart VII.

**Chart IV**


METHOD OF CHARTING
a=|A+B|
=NUMBER OF FORCE POLES PER FUNDAMENTAL POLE
c=$f_A+f_B$
=FREQUENCY OF "a" IN PER UNIT OF FUNDAMENTAL
b=|A-B|
=NUMBER OF FORCE POLES PER FUNDAMENTAL POLE
d=$f_A-f_B$
=FREQUENCY OF "b" IN PER UNIT OF FUNDAMENTAL
EXPLANATION OF CHART
SECOND SPACE-FORCE HARMONIC MOVING FORWARD AT FUNDAMENTAL SPEED (TWICE FUNDAMENTAL FREQUENCY)
UNIFORM FORCE IN SPACE. CONSTANT MAGNITUDE
FORCE HAVING TWICE THE FUNDAMENTAL NUMBER OF POLES CONSTANT IN MAGNITUDE
UNIFORM FORCE IN SPACE PULSATING IN TIME AT TWICE FUNDAMENTAL

The force waves under load will be larger since, as indicated under "assumptions", the maximum load current is twice the no-load current, all the stator harmonics and backward rotor harmonics will be twice as large. The forward rotor harmonics which do not exist at no load become almost as large as the others and not only are the magnitudes of the noise forces increased but the character of it is changed. (See the discussion of no-load versus load noise in appendix I.)

**Chart V. Graphical Explanation of Chart**
Two-Pole Motor Assumed




## Appendix I

In the calculation of magnetic force waves in the course of actual design work it is desirable to have a systematic method of work. This section of this paper describes such a method.

If time-phase relations are not important the equation for a magnetic flux wave as given in equations 3 and 7 expresses for us the following:

**Amplitude**
**Order (pitch, distribution)**
**Frequency**
**Direction**

If we deal with tooth harmonics the relation expressed in (2) and (5) is valuable in connecting amplitude with pitch so that if the pitch is known the amplitude is known. In such event only the pitch need be defined. If frequency be given a sign the symbol for frequency may be used to express both frequency and direction.

If we make these simplifications in our present case we may express any traveling wave by two numbers.* It is convenient to make these numbers "per unit" numbers as shown below. (By "per unit" is meant the expression of order and frequency as a ratio to the fundamental of each.)

$$W_a = \left[\frac{18}{-2}\right] = \cos\left[18\times\frac{\pi}{\lambda}+2\omega t\right] \quad (17)$$

If the upper number in the box be the order of the flux harmonic (the number of poles of the wave per fundamental pole) and the lower number the ratio of the harmonic frequency to the fundamental frequency, the wave $W_a$ is seen to have 18 times the fundamental number of poles and to be moving backward (because of the minus sign) at twice fundamental frequency.

The conventional expression for the wave is also given in (17) and it can be seen that the numerical coefficients of the conventional expression are used in the new nomen-

*NOTE: It is obvious that, if desired, a four-number system could be similarly set up representing phase relation, order, magnitude, and frequency-direction. For our present purpose the simplification is desirable.

**Chart VI. High-Frequency Noise Terms, 36–48 Slot Combination**

| ROTOR TOOTH HARMONICS | | STATOR TOOTH HARMONICS 17 +1 | 17 −1 | 19 +1 | 19 −1 | |
|---|---|---|---|---|---|---|
| 23 | | 6 | 6 | 4 | 4 | a |
| +2.5 | | 24 | 26 | 24 | 26 | |
| 23 | | 6 | 6 | 4 | 4 | b |
| +23 | | 22 | 24 | 22 | 24 | |
| 25 | | 6 | 6 | 6 | 6 | c |
| +2.5 | | 22 | 24 | 22 | 24 | |
| 25 | | 6 | 6 | 6 | 6 | d |
| +25 | | 24 | 26 | 24 | 26 | |

**Chart VII. Analysis of Major High-Frequency Force Waves With a 32- and a 36-Slot Stator**

| Stator | Rotor | Magnetic-Force Poles | | | Noise Frequency | | |
|---|---|---|---|---|---|---|---|
| 32 | 33 | 2 | 6 | 10 | 870 | 990 | 1,110 |
| | 34 | 4 | 12 | | 900 | 1,020 | 1,140 |
| | 35 | 2 | 6 | 14 | 930 | 1,050 | 1,170 |
| | 36 | 0 | 8 | 16 | 960 | 1,080 | 1,200 |
| | 37 | 2 | 10 | 18 | 990 | 1,110 | 1,230 |
| | 38 | 4 | 12 | 20 | 1,020 | 1,140 | 1,260 |
| | 39 | 6 | 14 | 22 | 1,050 | 1,170 | 1,290 |
| | 40 | 8 | 16 | 24 | 1,080 | 1,200 | 1,320 |
| 36 | 28 | 8 | 16 | 24 | 720 | 840 | 960 |
| | 29 | 6 | 14 | 22 | 750 | 870 | 990 |
| | 30 | 4 | 12 | 20 | 780 | 900 | 1,020 |
| | 31 | 2 | 10 | 18 | 810 | 930 | 1,050 |
| | 32 | 0 | 8 | 16 | 840 | 960 | 1,080 |
| | 40 | 0 | 8 | 16 | 1,080 | 1,200 | 1,320 |
| | 41 | 2 | 10 | 18 | 1,110 | 1,230 | 1,350 |
| | 42 | 4 | 12 | 20 | 1,140 | 1,260 | 1,380 |
| | 43 | 6 | 14 | 22 | 1,170 | 1,290 | 1,410 |
| | 44 | 8 | 16 | 24 | 1,200 | 1,320 | 1,440 |
| | 48 | 16 | 24 | 32 | 1,320 | 1,440 | 1,560 |

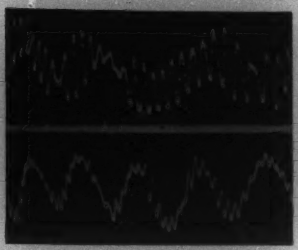


Figure 5. Cathode-ray oscillograms of stator-yoke vibration, 36–48 combination

clature except that the sign of the frequency term is reversed.

If it is desired to multiply two waves using the convention it is merely necessary to add the upper figure positive) to obtain $d$. The two waves are written together as at $e$.

If the two waves $W_a$ and $W_b$ are flux waves their product according to previous discussion is a pair of moving waves of force tending to bend the stator yoke into as many nodes as there are waves of force.

The present resultant force waves are seen to have 32 poles and 4 poles and to be moving respectively at twice fundamental frequency forward and at six times fundamental frequency backward. It will be noted that the numerical coefficient $^1/_2$ is dropped for simplicity in view of its existence in all similar product terms. A further simplification will be made for our present purpose in that after multiplication the sign will be dropped from the frequency terms since direction of rotation has no effect upon airborne noise in which we are primarily interested.

It was shown previously that a complete expression for the force waves of a motor would multiply each term of both the stator

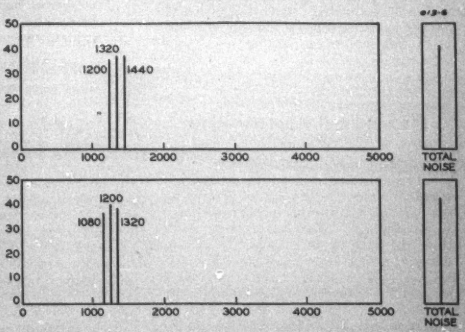
Chart VIII. Rotor Subharmonics

| STATOR SLOTS | ROTOR SLOTS | SUBHARMONIC POLES / SUBHARMONIC FREQ. | | | |
|---|---|---|---|---|---|
| 32 | 33 | 6 | 6 | 2 | 2 |
| | | +15.5 | +17.5 | −15.5 | −17.5 |
| | 34 | 8 | 8 | 0 | 0 |
| | | +16 | +18 | +16 | +18 |
| | 35 | 10 | 10 | 2 | 2 |
| | | +16.5 | +18.5 | +16.5 | +18.5 |
| | 36 | 12 | 12 | 4 | 4 |
| | | +17 | +19 | +17 | +19 |
| | 37 | 14 | 14 | 6 | 6 |
| | | +17.5 | +19.5 | +17.5 | +19.5 |
| | 38 | 16 | 16 | 8 | 8 |
| | | +18 | +20 | +18 | +20 |
| | 39 | 18 | 18 | 10 | 10 |
| | | +18.5 | +20.5 | +18.5 | +20.5 |
| | 40 | 20 | 20 | 12 | 12 |
| | | +19 | +21 | +19 | +21 |
| 36 | 40 | 12 | 12 | 4 | 4 |
| | | +19 | +21 | +19 | +21 |
| | 44 | 20 | 20 | 12 | 12 |
| | | +21 | +23 | +21 | +23 |
| | 48 | 28 | 28 | 20 | 20 |
| | | +23 | +25 | +23 | +25 |

Figure 6

Top—Noise spectrum taken on a four-pole (36–44) motor

Bottom — Noise spectrum taken on a four-pole (32–40) motor




and substract numbers of the same significance. For example:

$$W_b = \left|\frac{14}{4}\right| = \cos\left[14\times\frac{\pi}{\lambda} - 4\omega t\right] \qquad (18)$$

$$W_a \times W_b = \left[\frac{1}{2}\cos\left[32\times\frac{\pi}{\lambda} - 2\omega t\right] + \frac{1}{2}\cos\left[4\times\frac{\pi}{\lambda} + 6\omega t\right]\right] \qquad (19)$$

$$\left|\frac{14}{4}\right| \times \left|\frac{18}{-2}\right| = \left|\frac{32}{2}\right| + \left|\frac{4}{-6}\right| = \left|\frac{32}{2}\ \frac{4}{-6}\right| \qquad (20)$$

$b$ $a$ $c$ $d$ $e$

In equation 20 a horizontal addition is made to obtain $c$ from $a$ and $b$. A horizontal subtraction is made (in the direction to make and rotor Fourier series flux expression by itself and by each other term to form a second-order series of force waves. A multiplication form has been prepared and the operations performed for a 36–48-slot four-pole combination assuming no-load operation (chart III).

Inspection of the chart will show that when stator waves act together only "0" and "2" frequencies (0 and 120 cycles) exist. It is also apparent that when rotor waves act together high-frequency terms are produced (about 3,000 cycles) but the pitches of the waves are so short that it is extremely doubtful whether the resultant stator distortion could be detected.

All of the waves found in "$E$" and "$F$" will be found in "$A$" and "$B$" respectively and "$D$" will be found to be a replica of "$B$". Attention may therefore be concentrated upon section "$B$" of the chart when high-pitch noise is of interest.

If waves of extremely short pitch be discarded as being relatively ineffective we find ourselves with the same waves given in chart VI.

It is of interest to note that the four terms laterally adjacent to "$b$" and "$d$" result from forward-field rotor current and are, therefore, absent at no load and large under load. Terms adjacent to "$a$" and "$c$," however, are the result of backward-field rotor current and are large at no load as well as under load. The results of the analysis are statistically tabulated below in relation to the number of poles of force and the frequencies produced.

| 16 Poles | 24 Poles | 32 Poles |
|---|---|---|
| **No-load noise forces (cycles)** | | |
| 1,440 | 1,320 | 1,320 |
| 1,560 | 1,440 | 1,440 |
| | 1,440 | |
| | 1,560 | |
| **Additional-load noise forces (cycles)** | | |
| 1,320 | 1,320 | 1,440 |
| 1,440 | 1,440 | 1,560 |
| | 1,440 | |
| | 1,560 | |

If motor noise is measured at no load it would be expected that the 1,440-cycle and 1,560-cycle noises would predominate since the stator is much stiffer to 24-node and 32-node bending than to 16-node bending. Under load the 1,320-cycle noise should become pronounced, though, due to slip, it will be somewhat displaced in frequency.

All no-load noises should be reduced practically to zero by polyphase operation or the use of a proper capacitor. The introduction of a balancing capacitor (effective only under load) should be accompanied not only by a reduction in noise level but by the elimination of the highest of the three tooth frequencies, causing a change of about 120 cycles in the mean pitch of the high-frequency noise. Two-phase operation should show this clearly.

Chart VII has been prepared giving principal magnetic-force waves for all the possible slot combinations for a satisfactory re-

frigeration-machine motor assuming both 32- and 36-slot stators.

It is of special interest to notice that whenever force waves of zero poles occur there exist "geared" waves of the same number of poles on the rotor and stator. The existence of such waves is accompanied by standstill locking and high-speed rotating subharmonic waves of fundamental distribution and high-frequency tooth-harmonic interference. (Discussed briefly later.)

A two-pole magnetic force tries to displace the entire rotor thus producing shaft vibration, a four-pole force tries to distort the stator yoke into the form of an ellipse, etc. It is to be assumed that, other things being equal, a magnetic force of many poles is to be preferred to one of few poles; because of the greater effective yoke stiffness when the wave length is short. Any force wave having less than eight poles is likely to be bad for noise.

### Conclusions

It must be concluded that when a 32-slot stator is used the rotor is limited to 36 slots or 40 slots or more. If 36 slots are used it is questionable whether the locking and high-frequency interference (torque) noises can be kept from becoming a nuisance; spiral might control them. Above 40 slots there seems little reason to confine the slot combination to even slots if advantage is to be obtained by going to an odd number.

With a 36-slot stator the rotor possibilities are 28, 32, 40, 44, and higher. The remarks concerning the 36-slot rotor with a 32-slot stator apply to the 32- and 40-slot rotors with a 36-slot stator. Any rotor above 44 slots should be satisfactory except when the higher frequency of the produced noise is objectionable.

## Appendix II. Subharmonic Waves

When the number of squirrel-cage bars is small with respect to the pitch of the exciting wave of flux it is possible for a squirrel cage to produce a flux wave having fewer poles than the exciting flux wave. In certain cases the always large stator-tooth harmonics may react upon the rotor to produce a wave of flux of fundamental distribution but rotating at such speeds as 70,000 to 80,000 rpm in a four-pole motor operating at normal 1,725 rpm speed. Such subharmonic waves become very important in the noise of a motor and must be taken into account. The procedure after determining the flux waves present is exactly as already described except that the subharmonic waves are included in the calculation along with the fundamental and tooth-harmonic waves.

### Determination of Subharmonic Waves

Subharmonic waves may be determined as Chapman outlined in his book on induction motors by use of the equations:

$$S=\frac{2BK}{P_1}+h=\text{order and direction of subharmonic (direction referred to direction of } h \text{ with respect to rotor)} \quad (21)$$

$$f_s=\pm 1-\frac{2BK}{P_1}=\text{stator referred frequency in per-unit of fundamental frequency (single-phase stator)} \quad (22)$$

In the above equations:

$B$ = total number of rotor bars
$K$ = any positive or negative integer ($K=-1$ usually most important)
$P_1$ = number of fundamental poles
$h$ = order of a stator harmonic (use plus sign always)

The magnitude of a subharmonic depends upon the rotor impedance as well as the linkage of the rotor and the stator in so far as the generating stator harmonic is concerned. If the stator harmonic is of short pitch, as are most tooth harmonics, a slight amount of spiral greatly reduces the mutual and reduces the subharmonic. Even without spiral the amplitude will usually be found to be less than $A_1(1/h)^3$. Since the calculation of subharmonic magnitudes is somewhat involved it is felt that an outline of the method is not warranted here. The intent of these remarks is merely to call attention to the effect of subharmonics.

If the stator winding is "good" and the number of rotor slots is greater than the number of stator slots by $2P$, subharmonics may usually be neglected. If the number of rotor slots is less than this subharmonics should be studied.

Chart VIII lists subharmonics for 32- and 36-slot four-pole stators when various rotors are used.

A plus sign in (21) indicates a subharmonic wave moving in the same direction as the stator harmonic, $h$, with respect to the rotor. Since at normal forward operating speeds the rotor is always moving forward with respect to any stator harmonic, the movement of the stator harmonic with respect to the rotor is backward. Under these conditions, if the sign of (21) is negative, it means that the subharmonic is moving in the opposite or forward direction with respect to the rotor and, of course, forward also with respect to the stator. Since a plus sign for a frequency number in chart VIII indicates a wave moving forward with respect to the stator, chart VIII would therefore have a positive frequency number when (21) is negative.

### Nomenclature

$A_1$ = amplitude of fundamental stator flux wave
$A_{sf}$ = amplitude of fundamental rotor forward wave
$A_{NF}$ = amplitude of the $N$ forward tooth harmonic
$B$ = total number of rotor bars
$B_g$ = total density in the air gap at the point $x$
$f$ = frequency of primary excitation
$K$ = any integer
$n$ = number of stator slots per pole
$N$ = largest stator-tooth harmonic
$M$ = second largest stator-tooth harmonic
$P_1$ = fundamental number of poles
$R$ = largest (least poled) rotor-tooth harmonic
$s$ = per unit slip
$T$ = second largest rotor-tooth harmonic
$x$ = distance in inches measured peripherally around the air-gap surface
$\Delta F$ = force density (pounds per square inch)
$\lambda$ = fundamental pole pitch (inches)

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## Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

# Current Transformers and Relays for High-Speed Differential Protection, With Particular Reference to Offset Transient Currents

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**Synopsis:** Up to the present time, the only data generally available to protection engineers for determining the performance of current transformers have been the ratio and phase-angle curves of the current transformers in question. More detailed analysis of important high-speed differential protection problems has shown that these data are hopelessly inadequate for the purpose of determining the performance of current transformers during the starting period when the current wave may be fully offset. If the time constant for decay of the d-c component exceeds 0.05 second, large errors of transformation may be expected if standard current transformers are used. While it is possible to make special designs that will not saturate because of the d-c component in the current,[1] such designs are usually considerably oversize and expensive. Furthermore, space requirements and economy sometimes dictate that current transformers already installed be used if at all possible, even though it is known that their performance will be far from perfect. The problem then becomes one of determining the actual performance of existing current transformers, so that a suitable relay scheme may be chosen. It is the purpose of this paper to discuss the solution of this problem, and to present approximate methods of calculation not hitherto available. Attention is also given to the proper interpretation of the calculations with respect to relay operations, together with supporting test results.

THE PROBLEM of differential protection of generating-station busses is one which almost invariably requires calculation of current-transformer performance for asymmetrical currents, because of the long time constant of the generators. Figure 1 shows schematically a six-circuit bus protected by a simple overcurrent relay. The principle of differential protection indicates that, for an external fault at $X$, the current, $i_1$ through the relay should be zero. This is based upon the assumption that all the current transformers involved will perform perfectly. Inequalities are apparent at once, however, since it is seen that the transformer in circuit $F_6$ carries the total fault current, whereas the others each carry only a fraction of the total. The d-c component in the primary current, particularly troublesome when large generators are near the fault, aggravates the inequalities much more severely than is immediately obvious. For example, when conditions are severe, instantaneous peak values of $i_1$ may be of the order of 100 amperes when the symmetrical component of the total fault current is 100 amperes rms in terms of the secondary circuit.

The false differential current, $i_1$, which may exist when an external fault occurs at point $X$, is equal to the difference between the sum of the magnetizing currents of all the current transformers carrying current into the bus, and the magnetizing current of the current transformer carrying the total fault current away from the bus. (This can be derived from figure 1 by expressing each of the secondary currents in terms of their respective primary currents less the magnetizing currents of their respective current transformers, and solving for $i_1$, remembering that the sum of the currents entering the bus is zero for an external fault.) This forms the explanation for the inadequacy of ratio curves for this type of problem. It diverts the interest of the protection engineer at once from the question, "What will the secondary current be?" to the question, "What will the magnetizing current be?"

The authors have found that many protection engineers tend to underestimate the relative saturating quality of the d-c component of the asymmetrical current. Some have felt that, given a definite maximum instantaneous peak value for an asymmetrical current, it was only necessary to provide a current transformer whose performance would be satisfactory on symmetrical currents having the same peak values. This is definitely not true. For these reasons, the authors believe that the discussion immediately following is in order prior to the detailed mathematical treatment. This discussion is intended to convey a conception of the mechanics of d-c saturation in a form kept as graphical as possible.

## The Mechanics of Saturation

A convenient way to analyze the performance of the current transformer of figure 2*A* is by means of the equivalent diagram as shown in figure 2*B*. With a given value of primary current, $i$, the values of primary-winding resistance and leakage reactance are of no consequence, hence these values are not indicated in the final diagram for analysis (figure 3). Also, for convenience, the secondary-winding resistance and leakage reactance are lumped with the burden and shown as $R_2$ and $L_2$. The mutual inductance between primary and secondary windings is shown

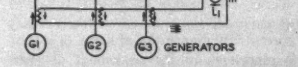


**Figure 1. Simple overcurrent differential protection of a six-circuit bus**

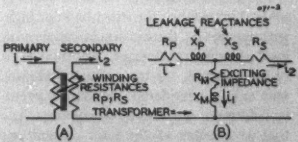


**Figure 2. Diagram of current transformer and its equivalent circuit**

by $L_1$, through which flows the magnetizing current, as indicated by $i_1$. It is possible to provide for the core loss current by including a suitable resistance in this branch, but this refinement is not necessary to provide sufficient accuracy for the problem at hand. This diagram is usable on the basis that the currents are expressed in terms of per cent of full-load current. Further, the diagram is usable

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1. For all numbered references, see list at end of paper.

in that, electrically, it satisfies the requirement that the primary current minus the magnetizing current must equal the secondary current. The physical significance of the current, $i_1$, flowing through the

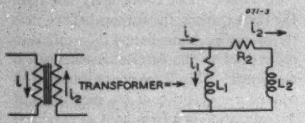



Figure 3. Simplified diagram of current transformer

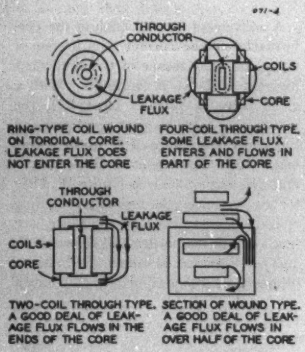

THROUGH CONDUCTOR
COILS
CORE
LEAKAGE FLUX
RING-TYPE COIL WOUND ON TOROIDAL CORE. LEAKAGE FLUX DOES NOT ENTER THE CORE
FOUR-COIL THROUGH TYPE. SOME LEAKAGE FLUX ENTERS AND FLOWS IN PART OF THE CORE
TWO-COIL THROUGH TYPE. A GOOD DEAL OF LEAKAGE FLUX FLOWS IN THE ENDS OF THE CORE
SECTION OF WOUND TYPE. A GOOD DEAL OF LEAKAGE FLUX FLOWS IN OVER HALF OF THE CORE

Figure 4. Leakage flux in different types of current transformers

mutual inductance, $L_1$, of figure 3, is that it represents in the equivalent diagram the vector difference between the primary and secondary currents in the actual transformer.

Inspection of figure 3 will show that the mutual impedance, $L_1$, must be kept high with respect to the burden impedance, if good current-transformer performance is to be expected. If the symmetrical current only is considered, standard current transformers are usually adequate. Actual asymmetry of the fault current requires consideration of a new and very important factor. The d-c component of the primary current must also divide between the parallel branches of figure 3. Since, to all practical purposes, there is very little impedance to direct current in the magnetizing branch, $L_1$, of the parallel circuit, the flow of direct current in this branch is retarded only by the inductive voltage generated by the time rate of change of the direct current, as it builds up in this circuit. The voltage which must be generated is determined by the voltage drop across the burden, $R_2$ and $L_2$, caused by the d-c component flowing through it. If the d-c time constant is long, this direct voltage must be maintained for a relatively long time, and it can only be done by a continuously increasing current through $L_1$ at a relatively high time rate of change. This must be done in one direction only, without the advantage of positive and negative half-cycles characteristic of alternating current. This means that the knee of the saturation curve for the inductance, $L_1$, may be reached within a few cycles, or within a fraction of a cycle in severe cases. When the iron core saturates, the effective value of the inductance, $L_1$, decreases to a fraction of the normal value. When this occurs, the ability of the mutual inductance to retard the flow of direct current through it collapses, so that practically all of the d-c component goes through $L_1$. This condition will continue until the d-c component has subsided, after which the transformer can again perform with its normal a-c characteristics. It is of interest and importance to note that during the time that the magnetizing branch, $L_1$, remains severely saturated by direct current, it also offers much less impedance to the flow of alternating current; consequently, it is to be expected that the percentage of the a-c component which is transmitted to the secondary will be materially less. These conclusions are borne out by oscillographic records which show that, when a current transformer is failing to reproduce faithfully the d-c component in the secondary, it is also breaking down in a-c ratio, even though its performance may be quite accurate on the same value of symmetrical current.

## Derivation of Formulas

Mathematical analysis of the current-transformer performance is based on the same equivalent circuit, shown in figure 3, and in fact, has already been worked out by Marshall and Langguth.[1] Their paper gives rules for keeping the flux density below the saturation value and for calculating performance, provided the transformer does not saturate, but, of course, cannot be used to indicate performance in cases where there simply is not room for the resulting design, or where existing transformers must somehow be used. The following analysis will be devoted to methods for calculating the performance, after saturation is reached. Important savings in space, as well as in weight and expense, may result if the analysis shows that current transformers which are far from perfect may still be adequate.

### General Considerations

Returning to figure 2*B*, it must be recognized that although the sum of the leakage reactances, $X_p$ and $X_s$, may be nearly constant and represent definite flux linkages, the effective division between $X_p$ and $X_s$ is different for every load condition, and they are individually practically impossible to determine.

Most problems deal with the "through" or "bar" type of current transformer, which can be so designed that the leakage flux which enters the core is negligible, and the following theory has, therefore, been worked out on the basis that the secondary leakage reactance is zero. The theory cannot be indiscriminately applied to wound-type transformers nor to through-type transformers with coils only on two legs of the core (see figure 4) without preliminary investigation of the relative amount of leakage flux.

The theory described assumes that the reactance of the burden is also zero. The justification for this is difficult to establish rigorously, but it can be readily estimated that once the d-c component of current is established (as it is during the first half-cycle) the inductance in the burden will present no obstacle to maintaining it, while the resistance in the burden acts against the direct current with a more or less continuous counter ($IR$) voltage. The

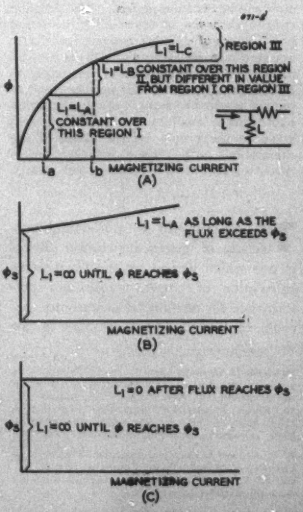



Figure 5. Approximations of the saturation curve

The true saturation curve may be approached as closely as may be desired

theory has been worked out and calculations made with inductance in the burden, and it has been found that it makes very little practical difference in the result if the inductance is neglected, at least for burden power factors of 80 per cent or more. Tests confirm this.

The value of the assumption that $L_2=0$ is that the numerical work of calculation is approximately halved. After an example has been worked out, the importance of this becomes obvious. In the short-cut method to be described later, the secondary inductance may be included, but it can be shown that it can be neglected with negligible error.

The final assumption is that the equivalent resistance of the magnetizing branch of the network is zero. Correctness of this assumption is more difficult to prove, but actual results indicate that it is always practically true.

### Fundamental Equations

The equivalent network to be analyzed is thus very simple, figure 3, and may be analyzed exactly as Marshall and Langguth have previously done, except that $L_2=0$.

The equation for the difference current will be the same as given by Marshall and Langguth (equation 15, corrected) in their paper, except to neglect $L_2$.

$$i_1=\frac{1}{R_2T_1}\epsilon^{-t/T_1}\int R_2 i\epsilon^{t/T_1}\,dt+C\epsilon^{-t/T_1} \qquad (1)$$

where $T_1=L_1/R_2$.

If the circuit is closed at the moment to get a fully offset primary current:

$$i=I(\cos\omega t-\epsilon^{-t/T}) \qquad (2)$$

Substituting for $i$ and performing the indicated integration gives:

$$i_1=I\left[\frac{\cos(\omega t-\Delta)}{\sqrt{1+(\omega T_1)^2}}-\frac{T}{T-T_1}\epsilon^{-t/T}\right]+C_1\epsilon^{-t/T_1} \qquad (3)$$

$$\Delta=\tan^{-1}\omega T_1$$

$$T_1=\frac{L_1}{R_2}$$

This equation is perfectly general, and is the one on which the calculation of exciting current will be based. Its limitation in actual use is that $L_1$ (and $T_1$) are assumed to be constant; in the actual problem the solution must be carried out into the region of saturation, and $L_1$ (and $T_1$) will vary.

## Step-by-Step Solution

### Three-Zone Saturation Curve

Any saturation curve can be represented as closely as may be desired by a number of straight lines. This makes it possible to consider the inductance constant in a given region, as in figure 5*A*. With such an approximate curve, the magnetizing current may be calculated by means of equation 3. The procedure is to begin at time, $t=0$, setting $L_1=L_A$, $i_1=0$, evaluate $C_1$, and calculate $i_1$ at various values of $t$. It must be remembered that each time that $i_1$ enters a new region, figure 5*A*, the value of $L_1$ must be changed correspondingly, and a new value of $C_1$ obtained. This procedure gives good results, but is very laborious, and quite impractical for most problems. Further simplification is desirable.

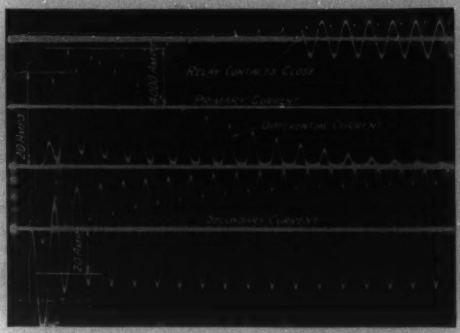


**Figure 6A. Oscillogram showing that nonsaturating current transformer (primary current) balanced against current transformer that saturates (secondary current) gives a false differential current**

Primary current, 4,000 amperes rms, $T=0.075$, ratio 1,000/5, test current transformer core area 1.69 square inches, secondary resistance 1.05 ohms

### Two-Zone Saturation Curve

It will usually be found that the exciting current will be negligible in its effect on the differential relay until the upper region of the saturation curve is reached. This justifies the assumption of a more simple shape of the saturation curve, as in figure 5*B*. The advantage of this shape is that $L_1$ is infinite until the "saturation" flux is reached, and the boundary conditions at the same time, $t_1$, at which $\phi_s$ is reached are: $t=t_1$, $i_1=0$. Returning to equation 5 in the paper by Marshall and Langguth, the flux will be (letting $L_2=0$ and writing $I_s$ for $N_pI_p/N_s$)

$$\phi=\frac{10^8I_s}{N_s}\left[\frac{R_2\sin\omega t}{\omega}+R_2T\epsilon^{-t/T}\right]+C \qquad (4)$$

The procedure of calculation will be:

1. Calculate the flux variation beginning at time, $t=0$, $\phi=0$. Evaluate $C$ accordingly, and calculate $\phi$ at several intervals of time, $t$, as necessary to determine the time, $t_1$, at which the flux will reach the "saturation" value, $\phi_s$.

2. The new boundary conditions to be used now in equation 3 will be $t=t_1$, $i_1=0$. Evaluate $C_1$ and calculate $i_1$ at suitable intervals of time. Inspection of the equation shows that $i_1$ may be maintained at a positive value for a considerable length of time if the values of $t$, $C_1$, and $T$ are suitable.

3. However, $i_1$ will eventually pass through zero. When it does at time, $t=t_2$, we must return to the equation 4 for $\phi$ and substitute the boundary conditions, $t=t_2$, $\phi=\phi_s$. The variation of $\phi$ must then be calculated. Usually; it will return to the "saturation" value of $\phi_s$ within a fraction of a cycle, say at time, $t_3$.

4. At time, $t_3$, $i_1=0$, determine a new value of $C_1$ and continue calculation of $i_1$.

This procedure might appear to be fully as difficult as that of the first method. Actually, it is much easier, and usually gives results which are not appreciably different.

If circuit constants are such that the exciting current (paragraph 2 above), is maintained at a positive value for a number of cycles, equation 3 shows that this exciting current is composed of a sinusoidal component with two superimposed d-c components. Unless the top of the saturation curve has an appreciable curvature, there will be few harmonic components in the exciting current. The variation of flux may occur over a relatively short zone along the top of the saturation curve, which may be nearly straight. Of course, the actual flux variation is always along a superimposed hysteresis loop, and the equivalent degree of curvature with the resulting harmonic components cannot be practically determined on any exact basis. However, tests show that the actual differential current may often be very nearly sinusoidal.

### Flat-Top Saturation Curve

A still more simple method is to assume that the saturation curve has a flat

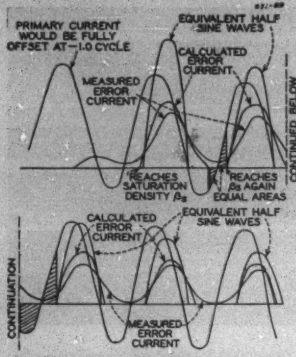



**Figure 6B. Check of calculated error current against measured error current of figure 6A**

The lower section of the figure is a continuation of the upper section. The "calculated error current" was calculated by the step-by-step method, equation 3 and sloped-top saturation curve, and the "equivalent half sine waves" were calculated using equation 12

Constants for calculated error current: $I=28.3$, $T=0.075$ $\omega L_1$ corresponding to slope of top of saturation curve $=1.37$, $R_1=1.05$, $A=1.69$ square inches .

top, so that $L_1$ will be zero after saturation (figure 5C) and the current equation will become:

$$i_1 = I(\cos \omega t - \epsilon^{-t/T})$$

This is the same as the expression for the primary current, and shows, as would be expected, that if the saturation is complete at density, $\phi_s$, there is no further reproduction of current in the secondary circuit until the time during the cycle when the primary current again passes through zero. At this time, the flux will tend to decrease below $\phi_s$ and the primary current will, thereafter, be perfectly reproduced until the flux once more increases to $\phi_s$.

Figure 6B shows the exciting current as measured, and as calculated according to the sloped-top, and the flat-top saturation curve, compared with test values, for a given example. It can be seen that the calculated values according to both methods are in fair agreement with the test values.

## Approximate Formulas

All these methods involve a great deal of numerical work. They are entirely too difficult for use in making the large number of preliminary estimates of performance which must be made during the study of a system of protection for a given bus layout. A still more simple solution is based on some rather bold assumptions. The justification of these assumptions will be shown to be two-fold:

1. The assumptions will be such that the final result will be pessimistic.

2. The results will agree sufficiently well with actual tests to be generally useful.

Returning to figure 6B it will be seen that the measured exciting current exhibits the following characteristics:

1. The area under the test current wave is very nearly the same as the area under the calculated current wave.

2. The exciting current wave form is approximately that of a half-wave rectified current.

These characteristics are shown in a large number of oscillograms, some of which are shown in figures 6A, 10A, and 10B.

From these considerations we will make the following assumptions:

1. The exciting current can be calculated and dealt with on the basis that it will always be a half sine wave.

2. The magnitude of it can be calculated on the basis that the area under the half wave will equal the area under the exciting current wave calculated by the previously described method.

The meaning, and the advantage of assumption 2 will be apparent from the consideration that the area of the exciting current wave can be determined fairly simply from the fundamental equation:

$$N\frac{d\phi}{dt}10^{-8} = R_2 i_2$$

$$N\phi 10^{-8} = 10^{-8}\int N d\phi = R_2 \int i_2 dt \qquad (5)^*$$

and the consideration that $\phi$ will be at the saturation value at both beginning and end of a cycle, and that if the integration is from beginning to end, $N\phi$ must, therefore, be zero. The equation then becomes simply:

$$R_2 \int_{t=(n+1)T_0}^{t=nT_0} i_2 dt = 0 \qquad T_0 = \frac{1}{f} \qquad (6)$$

However, the actual integral of an asymmetrical primary current over a cycle is obviously not zero. The meaning of this is that the whole value of the integral of primary current is exciting current, and will flow through the differential circuit. This integral is easily evaluated and can be shown to be (see appendix I):

$$\int_{t=(n+1)T_0}^{t=nT_0} i dt = IT\epsilon^{-nT_0/T} \qquad (7)$$

for any given cycle, $n$. Now, if the area under the exciting wave is $IT\epsilon^{-nT_0/T}$ according to (7), the magnitude of its peak value can easily be determined, if the assumption is maintained that the exciting current will appear as a half sine wave. The area under a half sine wave is (see appendix I):

$$A = \frac{PT_0}{\pi} \qquad (8)$$

where

$P$ = peak value
$T_0$ = time of one cycle

If the area is given by (7), the peak value can be obtained from (8) and (7).

$$P = \frac{\pi A}{T_0} = \pi I \epsilon^{-nT_0/T} \qquad (9)$$

This expression for value of any exciting current peak at the $n$th cycle can be very quickly evaluated.

Determination of the time at which the saturation value of flux is reached can be made from equation 4. This equation cannot be solved for $t$ as it stands, but if we make the pessimistic assumption that the sinusoidal component is always at its maximum value—

$$\frac{R_2 \sin \omega t}{\omega} = \frac{R_2}{\omega}$$

then the equation can be solved for $t$, giving

$$t = -\frac{T}{0.434 T_0}\log\left[1 - \frac{\beta_s NA}{10^8 R_2 T I} + \frac{1}{\omega T}\right] \qquad (10)$$

If an impedance, $Z_D$, is connected into the differential circuit, it obviously will reduce the differential current. If the resistance were zero, the effect of inductance would be to reduce the variation in current, but to allow about the same magnitude of d-c component. If the inductance were zero, the resistance would continuously oppose the current, reducing it at every point on the wave.

If the differential current is calculated on the basis that the inductance in the differential circuit is negligible, the calculated value will certainly be somewhat too high, and the result will be in error on the conservative side. Referring to figure 9, we can rewrite (5)—

$$e_2 = \frac{Nd\phi}{dt}10^{-8} = R_2 i_2 - R_D i_1 \qquad (11)$$

Considering, as before, that $\phi$ will have to be the same, and equal to $\phi_s$ at the end of each cycle, it can be shown that (ap-

* $L_2\frac{di}{dt}$ may be included in this equation, but it can be shown that the resulting integral $Ldi$ will be negligible for any usual problem.

pendix II) the differential current will be a fraction of the value calculated from the assumption that the resistance in the differential circuit is zero, or

$$P = \pi I \epsilon^{-\pi r_s/T} \frac{R_2}{R_D + R_2} \text{ (peak amperes)} \quad (12)$$

The methods used may seem to lack mathematical rigor. Indeed they do, but the assumptions are all uniformly pessimistic, and cannot well cause errors which destroy the practical value of the result. Comparison with tests show that the results are sufficiently accurate to be useful.

## Relay Characteristics

The operating characteristics of relays are usually given in terms of symmetrical sine-wave quantities. Also, when current-time curves are taken, the current is usually left on until after the contacts have closed and the time determined. Consideration of the characteristics of the expected differential current reveals at once that it is not always sinusoidal nor symmetrical, and that it does not necessarily last for a length of time sufficient to cause the relay contacts to close, depending, of course, upon the time setting of the relay being used. For the differential problem, additional data are needed. These cover relay performance on altered wave forms involving various amounts of d-c and current-time curves wherein the current is applied only for a limited time. The latter curves will be termed "impulse curves" for convenience.

It is impossible to duplicate in the relay testing laboratory all of the possible currents which may occur in the differential circuit when all the variations between applications and between different possibilities for one application are considered. The best that can be done is to take data of a general nature which may be approximately interpreted for the particular application. Consideration of a large number of test oscillograms lead to the following conclusions:

1. The differential current for two or more cycles may be fairly represented in many cases by a fully and continuously offset sine wave. These few cycles, then, represent those test conditions wherein the harmonics present in the differential current are of minor consequence. The condition is easily set up by passing both steady-state direct current and sine-wave alternating current through the relay coil at the same time.

2. Subsequent cycles of the differential current may be fairly represented by half-wave rectified current. This approximation is sufficiently accurate until the differential current has subsided to a point where it is negligible in comparison with the original peak values.

A comparison of a standard current-time curve with impulse curves is given in figure 8 for a standard-type *COH* overcurrent relay. Each of the four curves was taken with the same tap and time-lever setting. The abscissas are plotted in terms of peak amperes rather than rms amperes in order that the approximate formula (9) or (12) for differential current may be most useful. Curve *a* is the usual current-time curve where the current is not interrupted until after the contacts close. For curve *b*, however, sine-wave 60-cycle current was applied only for the length of time shown by the time scale, and then interrupted. After the current was interrupted, the contacts closed due to kinetic energy stored in the disk. The total elapsed time from the application of current until the contacts closed is not shown by the curve at all. Thus, this curve is an "impulse curve", indicating a product of current and time which will store just sufficient kinetic energy in the relay disk to cause the contacts to close. Curve *c* is a similar impulse curve, except that half-wave rectified current was used. Curve *d* is a similar curve for a fully offset sine wave, where the direct current through the relay was made equal to 1.414 times the a-c sine-wave amperes. Curves *c* and *d* compared with curve *b* show the effect of a d-c component. Also, for the same peak-current values, curves *c* and *d* have less rms and 60-cycle component values. Curves *c* and *d* differ from each other because of the proportion of the direct current being different and because there are harmonics in the half-wave current.

## Confirming Tests

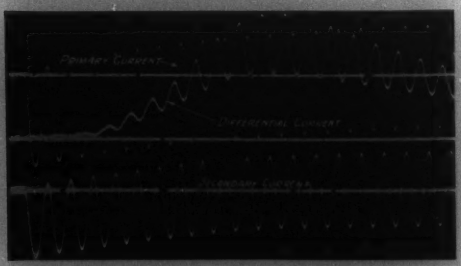
The approximate methods of calculating the current-transformer performance, as given, and the proper interpretation of the results in terms of impulse characteristics of the relays would have no value, of course, if it were not possible to verify the predictions made by means of suitable tests. Confirming tests have been made with results as given below.

### Test Setup

Figure 9 shows the essential details of the test setup which was used. The circuit for demagnetizing the current transformers between tests is not shown. The nonsaturating current transformer shown was liberally designed so that it would not saturate under any of the test conditions. For this reason, the oscillographic record of $i$ was taken as the true picture, in terms of the secondary, of the primary current. At the same time, the current, $i$, may be taken to represent the total output of any number of current transformers carrying current into a bus for an external fault, as in figure 1, on the basis that these current transformers do not saturate. This is a legitimate simplification of test setup, since nonsaturation of the input current transformers gives the maximum difference current, $i_1$, for a given saturation of the outgoing current transformer. Thus, the most pessimistic condition is arrived at at once with a decided simplification of test.

The resistor, $R_2$, was used to obtain various degrees of saturation of the test current transformer. The resistor, $R_D$, was

**Figure 7. Test oscillogram showing error current with high percentage of direct current**



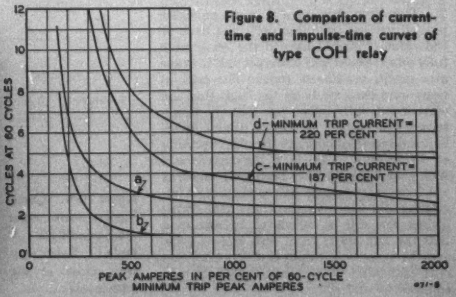



**Figure 8. Comparison of current-time and impulse-time curves of type COH relay**

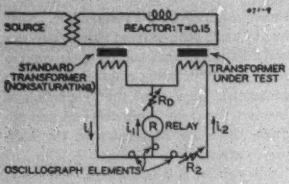



Figure 9. Diagram of test circuit

used to explore the possibility of preventing the false operation of a simple overcurrent differential relay by this means, and to check the accuracy of equation 12 showing the reduction in differential current expected.

As usual in tests of this kind, the current wave shape which can actually be obtained is not the perfect shape assumed in the theory, and the test results have to be properly interpreted to take the actual variation into account. The actual wave departs from the theoretical as follows:

1. It is never perfectly offset.

2. The output from a power transformer will contain not only a d-c component in proportion to the primary d-c component, but also a secondary d-c component determined by the constants of the secondary circuit. As a result, the secondary current, if initially offset on one side of zero, always becomes slightly offset on the opposite side before the transient finally disappears. The apparent decrement toward the end of the transient is higher than at the beginning, and higher than would be predicted from the true time constant $L/R$ of the circuit.

3. There seems to be a higher decrement over the first cycle of current, probably due to the contact not being solidly closed initially.

The test results were, therefore, analyzed as follows:

1. The time constant was determined by plotting the logarithm of the average value of current. When the time constant departed to an appreciable extent from the true value (toward the end of the transient) the test and calculation do not agree, and this fact was simply accepted as unavoidable.

2. The logarithm of the average value plotted against time was projected back to the value it should have if the wave were fully offset, and it was always found to occur at a negative value of time. The calculations were then made on the basis that the current was fully offset, but that the transformer flux started at zero at some equivalent time corresponding to the real beginning of the current. That is, if the current was such that it would have been fully offset at $-1.0$ cycle (one cycle before the actual beginning) the time of saturation of the transformer can still be calculated by assuming that the flux starts from zero at $t=1$ cycle and the successive values of differential current calculated using $n+1$ instead of $n$ in equations 9 and 12.

Table I

$I=28.3$ $R_s=1.05$ $R_D=0.38$
$P$ = Peak Value of Differential Current

| $n_{osc}$* | $n_{eff}$† | $P=\frac{1.05_{\nu}I_e-nT_s/T}{1.43}$ P Test Figure 10A | Calculated Cycles From Figure 8c: From Calculated P | Calculated Cycles From Figure 8c: From Test P | Reciprocals**: Column 5 | Reciprocals**: Column 6 |
|---|---|---|---|---|---|---|
| 0 | 1 | 2.04 | | | | |
| | | Saturation occurs here | | | | |
| 1 | 2 | 41.4 | 17.9 | 3.2 | 4.8 | 0.310 | 0.208 |
| 2 | 3 | 33.3 | 18.36 | 3.5 | 4.7 | 0.286 | 0.213 |
| 3 | 4 | 26.6 | 16.0 | 3.9 | 5.4 | 0.256 | 0.185 |
| 4 | 5 | 21.3 | 13.8 | 4.2 | 6.3 | 0.238 | 0.159 |
| 5 | 6 | 17.1 | 11.6 | 5.0 | 7.9 | 0.200 | 0.127 |
| 6 | 7 | 13.7 | 9.88 | 6.5 | 9.5 | 0.154 | 0.105 |
| 7 | 8 | 11.0 | 8.31 | 8.4 | 12.5 | 0.119 | 0.080 |
| 8 | 9 | 8.75 | 6.75 | 12.0 | 18.0 | 0.083 | 0.055 |
| 9 | 10 | 7.02 | 5.64 | 18.0 | 24.0 | 0.055 | 0.042 |
| 10 | 11 | 5.67 | | 24.0 | | 0.042 | |
| | | | | | | 1.743 | 1.174 |

* $n_{osc}$ denotes the number of the cycle on the oscillogram.

† $n_{eff}$ denotes the number of the cycle on counting from time, $t=-1.0$ cycle where the current would have been fully offset.

** The reciprocals indicate a percentage of the energy required to operate the relay. Thus, if three cycles of a given peak current are required to close the contacts, then each peak delivers one-third of the total energy needed.

This sort of interpretation is awkward and not as straightforward and clear as might be desired, but is hardly to be avoided. If an a-c generator is used to supply the current, the difference between transient and subtransient reactance will reduce the initial a-c component, with the result that a wave which is initially fully offset may be more than fully offset during the second or third cycles, which will also require interpretation. It is obvious that the possible impulses of differential current can safely be calculated on the basis that the a-c component is maintained at the value corresponding to the subtransient reactance. Therefore, whether the current source is a generator or a transformer, the calculated differential current will always be somewhat higher than the actual value, providing that the current is based on the subtransient reactance of the generator.

The perfect current transformer used as a standard had about ten times the cross section of core and about one-fifth the resistance in its circuit of the transformer under test, and calculation showed that its flux density never exceeded the value corresponding to maximum permeability, so that it can safely be considered to be perfect. The other transformers in an actual differential protection circuit may not be perfect. If they are not, the actual differential current will be even less, and a perfect transformer balanced against a poor one represents a worst possible condition.

Taking all these considerations into account, a large number of tests were made and compared with calculations.

## Test Results

The first set of tests was made with negligible resistance in the differential

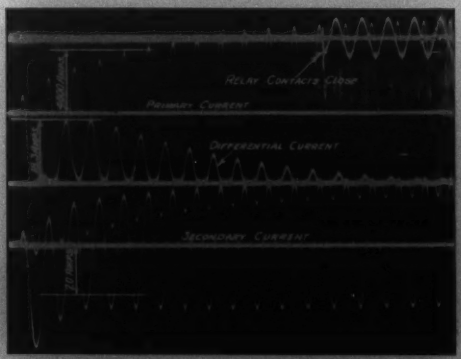



Figure 10A. Oscillogram made under the conditions of table I. Relay contacts close at the 12th cycle

circuit. The differential current was calculated according to equations 3 and 4, and a very good agreement obtained (figure 6). It was also calculated according to equation 12, and it can be seen that the equivalent half sine waves are much larger than test values to begin with, but are in fairly good agreement with test after the first few cycles.

The next step was to introduce resistance into the differential circuit. With a burden resistance of 0.82 ohm and a differential resistance of 0.38 ohm, the oscillogram of figure 10*A* was taken. The primary current lacked one cycle of being fully offset; that is, it would have been fully offset at −1.0 cycle. The time to saturation, calculated by equation 10, is 0.95 cycle. Taking this as 1.0, the equivalent time at which saturation would occur is actually about 2.0 cycles, and the successive calculated peaks (equation 12) of differential current are given in table I with the test values scaled from figure 10*A* for comparison.

The number of cycles which each peak would have taken to operate the relay (taken from figure 8) are given in columns 5 and 6 of table I, and the reciprocals of the numbers of cycles in columns 7 and 8. The sums of these columns are 1.74 and 1.17 respectively, and both indicate that the relay should operate. The relay actually operated about once in six times of application of current, and always operated when the current was offset as in figure 10*A*.

When the differential resistance is increased to 0.75 ohm, the oscillogram, figure 10*B* results and the corresponding peaks are given in table II. The sum of the reciprocal column based on calculated current indicates that the relay should operate. Actually, the relay could not be made to operate.

These tests indicate a considerable factor of safety. A large number of tests and calculations have been made, some of which show no factor of safety at all, and one test showed an actual operation when the calculated sum was only 0.8. This test indicates that if nonoperation is to be guaranteed, the sum of the reciprocal column should be held to something less than 0.8. A sum of 0.5 has been taken as a very safe value. If saturation occurs during the first two or three cycles, consideration of the possible differential current shows that each peak will have to last longer than one-half cycle and will, therefore, have a smaller peak value. Therefore, a larger factor of safety can be counted on if saturation occurs very soon than if it occurs later.

The test results which can be presented here are necessarily limited, so that they cannot adequately cover the entire range of possibilities. A large number of tests have been made, however, with sufficient results to justify the methods covered in this paper and are sufficiently general to warrant the following discussion.

In figure 10, for example, it is noted that the first few cycles of differential current are composed almost entirely of a d-c component and a sine-wave component.

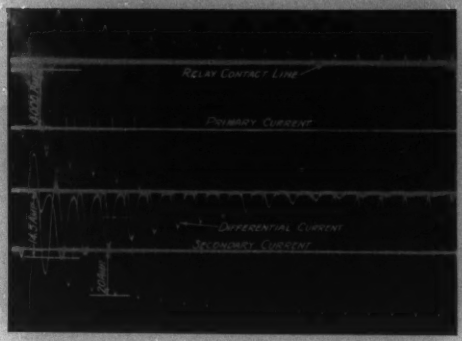



**Figure 10B. Oscillogram made under the conditions of table II. Similar to table I, except that $R_D = 0.75$ ohm. The relay does not operate**

Obviously, its form is different from half wave, but the half-wave impulse curve of the relay was used in predicting relay operation. A better prediction could have been made by using impulse curve 8*d* for the first few cycles. However, curve 8*d* shows that the combined direct current and sine wave is less effective in operating the relay, and it is thus concluded that the use of curve 8*c* errs on the conservative side. From the point of view of simplification, as well as insuring that errors will always be on the conservative side, it is better to use curve 8*c* only, neglecting curve 8*d*.

## Other Relays

The tests described were made with a simple overcurrent relay. In many cases, such a relay is not adequate for bus differential protection. The type *CA*-6 relay, which is a ratio-differential relay of the variable-ratio type, may be used where the requirements are more severe. With this relay, the same method of calculation of the peak values of the differential current may be used, of course. In considering the impulse characteristics, however, the effect of through fault current restraint is very important and helpful in allowing a much greater degree of current transformer saturation without causing a false tripping operation for a through fault. The impulse curves for the type *CA*-6 relay are quite similar to curve *c* of figure 8, except that they are moved considerably to the right, even with moderate restraint values.

## Conclusions

1. The methods of approximate calculations outlined provide a tool for the analysis of current-transformer performance which has not been available previously.

2. The resulting predicted current in differential relay circuits is sufficiently accurate

**Table II**

$I = 28.3$ $R_t = 1.05$ $R_D = 0.75$
$P$ = Peak Value of Differential Current

| Note | $n_{eff}$ | $P = \frac{1.05}{1.8} \times Ie^{-nT_2/T}$ | P Test Figure 10B | Calculated Cycles From Figure 8c: From Calculated P | Calculated Cycles From Figure 8c: From Test P | Reciprocals: Column 5 | Reciprocals: Column 6 |
|---|---|---|---|---|---|---|---|
| 0 | 1 | | 4.5 | | | | |
| | | Saturation occurs here | | | | | |
| 1 | 2 | 32.8 | 14.3 | 3.6 | 6.0 | 0.278 | 0.167 |
| 2 | 3 | 26.4 | 13.9 | 3.8 | 6.4 | 0.263 | 0.156 |
| 3 | 4 | 21.1 | 11.6 | 4.2 | 8.0 | 0.238 | 0.125 |
| 4 | 5 | 16.9 | 10.0 | 5.0 | 9.5 | 0.200 | 0.105 |
| 5 | 6 | 13.6 | 8.6 | 6.4 | 12.0 | 0.156 | 0.083 |
| 6 | 7 | 10.9 | 7.5 | 8.4 | 15.3 | 0.119 | 0.066 |
| 7 | 8 | 8.73 | 6.85 | 12.0 | 20.6 | 0.083 | 0.049 |
| 8 | 9 | 6.95 | 5.28 | 18.0 | | 0.056 | |
| | | | | | | 1.393 | 0.751 |

for determining relay schemes and settings because the approximations which it has been necessary to make have been uniformly made on the pessimistic side.

3. The use of impulse curves of relays is of material value in reducing the amount of safety factor to allow because of unknown factors.

4. It is felt that the agreement between calculated results and test results, while not perfect, is sufficiently close to warrant the use of the method by protection engineers. Because of the variations noted, however, it is recommended that a safety factor of about 2 should be applied in relay work.

## Appendix I

Evaluation of

$$\int_{t=(n+1)T_0}^{t=nT_0} idt$$

$$i = I(\cos \omega t - \epsilon^{-t/T})$$

$$\int_{t=(n+1)T_0}^{t=nT_0} idt =$$

$$I\left[\frac{\sin \omega t}{\omega} + T\epsilon^{-t/T}\right]_{t=(n+1)T_0}^{t=nT_0} =$$

$$IT\left[\epsilon^{\frac{-nT_0}{T}} - \epsilon^{\frac{-(n+1)T_0}{T}}\right] =$$

$$IT\epsilon^{\frac{-nT_0}{T}}\left[1 - \epsilon^{\frac{-T_0}{T}}\right]$$

$T/T_0$ must be at least 3 in any problem of importance, because if the transient has a time constant less than three cycles long, it may usually be neglected. Hence, $T_0/T$ will be less than 0.33 and if we write the series for $\epsilon^{-T_0/T}$:

$$\epsilon^{-T_0/T} = 1 - \frac{T_0}{T} + \left(\frac{T_0}{T}\right)^2 \cdot \frac{1}{\underline{2}} \ldots \text{etc.}$$

and

$$\frac{1}{\underline{2}} \cdot \left(\frac{T_0}{T}\right)^2$$

and higher terms can be neglected.

Hence:

$$\int_{t=(n+1)T_0}^{t=nT_0} idt = IT\epsilon^{-nT_0/T}$$

Evaluation of area under a half sine wave of peak value $P$:

$$\text{Area} = P\int_{t=0}^{t=\pi/\omega} \sin \omega t dt$$

$$= P\left[-\frac{\cos \omega t}{\omega}\right]_0^{\pi/\omega}$$

$$= \frac{2P}{\omega} = \frac{2P}{2\pi f} = \frac{PT_0}{\pi}$$

If the area of the integral

$$\int_{t=(n+1)T_0}^{t=nT_0} idt = IT\epsilon^{-nT_0/T}$$

is to be set equal to the area under the equivalent half sine wave, $PT_0/\pi$:

$$\frac{PT_0}{\pi} = IT\epsilon^{-nT_0/T}$$

the equivalent peak value is $P = \pi I\epsilon^{-nT_0/T}$.

## Appendix II

Derivation of equation 12, considering effect of resistance in differential circuit: Continuing from equation 11, and following the same reasoning as in going from equation 5 to equation 7:

$$e_s = N\frac{d\phi}{dt}10^{-8} = R_2 i_2 - R_D i_1$$

or

$$N\frac{d\phi}{dt}10^{-8} = R_2 i_2 - R_D i_1$$

$$N\phi = N\int d\phi = 0 = R_2\int i_2 dt - R_D\int i_1 dt$$

$$\int i_2 dt = \frac{R_D}{R_2}\int i_1 dt$$

but

$$i_1 = i - i_2$$

and

$$\int i_1 dt = \int idt - \int i_2 dt = \int idt - \frac{R_D}{R_2}\int i_1 dt$$

Then

$$\int i_1 dt = \frac{R_2}{R_2 + R_D}\int idt$$

As in appendix I, if we express the area,

$$\int_{t=(n+1)T_0}^{t=nT_0} i_1 dt = \frac{PT_0}{\pi}$$

the equivalent half sine wave and

$$\int_{t=(n+1)T_0}^{t=nT_0} idt = IT\epsilon^{\frac{-nT_0}{T}}$$

we have

$$\frac{PT_0}{\pi} = \frac{R_2}{R_2 + R_D}IT\epsilon^{\frac{-nT_0}{T}}$$

and

$$P = \frac{R_2}{R_2 + R_D}\pi I\epsilon^{\frac{-nT_0}{T}} \qquad (12)$$

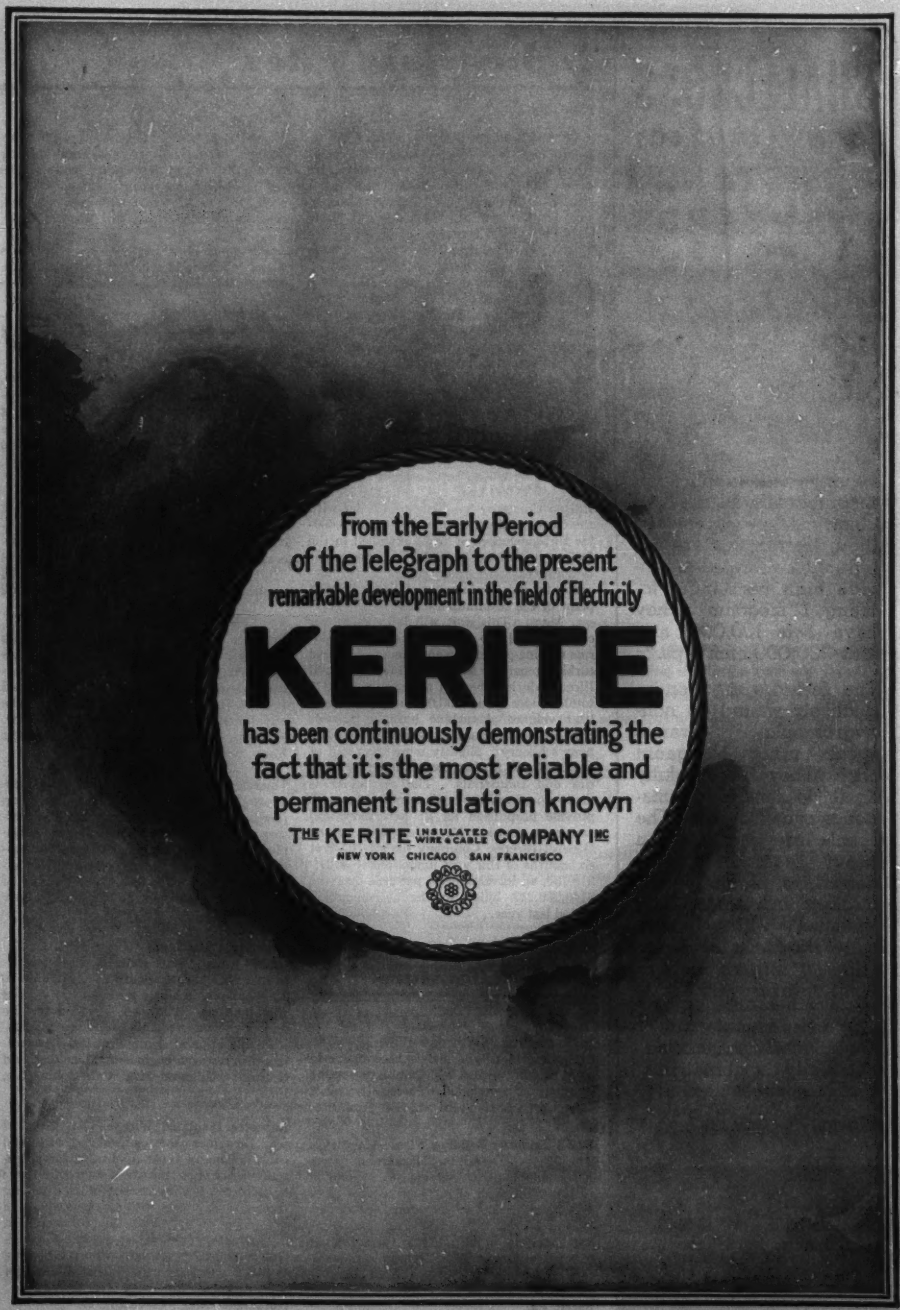
## References


1. Current-Transformer Performance Under Transient Conditions, Marshall and Langguth. AIEE Transactions, October 1929.

2. Considerations in Applying Ratio Differential Relays for Bus Protection, R. M. Smith, W. K. Sonnemann, and G. B. Dodds. AIEE Transactions, June 1939.


## Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.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# Industrial Notes

**Electrical Equipment Sales.**—The Westinghouse Electric & Mfg. Company's lighting division, Cleveland, Ohio, has received an order from the Allison plant of General Motors Corporation, totaling approximately $50,000, for fluorescent lighting fixtures. . . . .A contract has been awarded to the Allis-Chalmers Mfg. Company, Milwaukee, Wis., by the United States Department of Interior, for four transformers, totaling $426,000, for the Phoenix Terminal substation. They will be among the largest transformers ever built by Allis-Chalmers, and are to be connected to the 154,000-volt transmission line from Parker Dam on the Colorado River in Arizona, and will supply 69,000 and 12,500 volts for the power systems of the Salt River Valley Water Users Association and of the Central Arizona Light & Power Company. Each of the 3-winding, single-phase units is equipped with load ratio control and has a rating of 30,000 kva. . . . . The Detroit Edison Company has placed an order with the General Electric Company for a 75,000-kw turbine-generator to be installed in the Delray station late in 1941. Another recent General Electric order covers a turbine-generator unit for installation in the present plant of the Montaup Electric Co., Somerset, Mass. This unit will be suitable for carrying loads up to 25,000 kw. . . . . Marine turbine-propulsion equipments and land turbine-generator sets ordered from General Electric during the first six months of 1940 totaled more than 2,000,000 hp. This half-year volume of turbine business exceeds that of any comparable period in the company's history. Slightly more than half of the 2,000,000 hp has been ordered by utilities and industrials. The remainder is made up of marine equipments ordered to provide propulsion for 25 new navy and merchant vessels. Net sales billed by the General Electric Company during the first six months of this year amounted to $191,619,132, an increase of 31 per cent over the $146,299,212 billed in the corresponding period last year.

## Trade Literature

**Disconnecting Switches.**—Bulletin 68, 8 pp. Describes type BB-1, hook-operated disconnecting switches. Complete catalog information is included. Pacific Electric & Mfg. Corp., 5815 Third St., San Francisco.

**Small Diameter Building Wire.**—Handbook 200, 32 pp. Describes "Hazakrome" type SN small diameter building wire available in a full range of sizes from 14 A.w.g. to 4/0 inclusive, and in six permanent colors. Wiring tables, with engineering and comparative data on old and new type conductors as to size, loading, installation, costs, etc., are included. The Okonite Co., Hazard Insulated Wire Works Division, Wilkes-Barre, Pa.

**Steel Poles.**—Bulletin HD-306, 4 pp. Describes "Monotube" steel poles and lighting standards. Many installation photographs are included, illustrating the various services for which these poles are adapted. The Union Metal Mfg. Co., Canton, Ohio.

**Instruments.**—Cat. 4120, 8 pp. Describes panel type 3- and 4-inch round and square instruments, including a-c and d-c ammeters and voltmeters, single and polyphase wattmeters, radio frequency ammeters and milliammeters. Roller-Smith Co., Bethlehem, Pa.

**Phase Sequence Indicator.**—Bulletin 400. Describes the Knopp phase sequence indicator, primarily for indicating the order of succession in time of the different voltage peaks of a multiphase supply. Electrical Facilities, Inc., 4224 Holden St., Oakland, California.

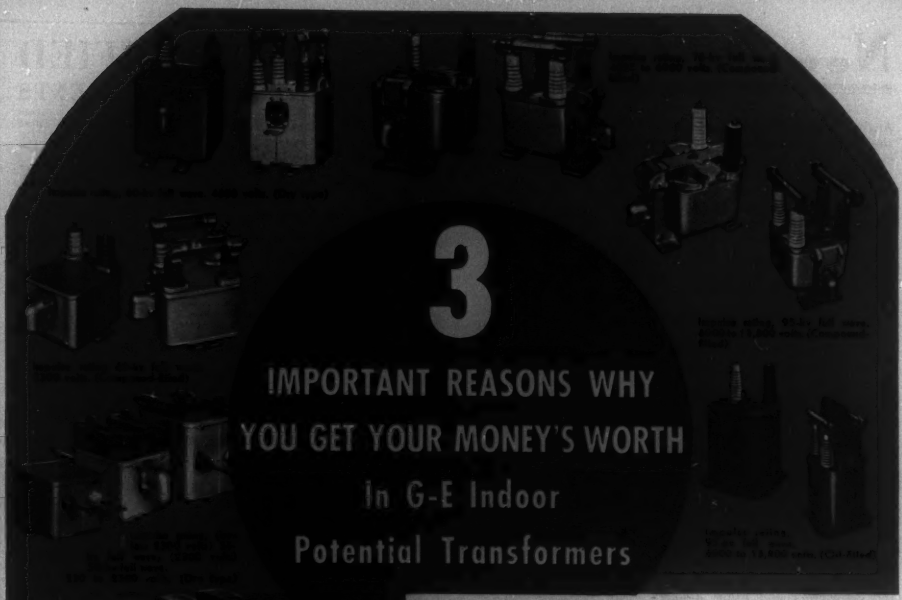
**Thermocouples.**—Catalog N-33A(6), 40 pp. Describes a comprehensive line of thermocouples and assemblies, with parts and accessories. Includes information of general utility on the correct choice of couples for all applications. Leeds & Northrup Co., 4962 Stenton Ave., Philadelphia, Pa.

**Portable Voltmeter.**—Bulletin. Describes a new triple-range voltmeter; ranges 0-150/300/750 volts; accuracy $\frac{1}{2}$ of 1 percent; scale length $5\frac{1}{4}$ inches. Designed for a-c use but may be employed on d-c circuits with a slight sacrifice in accuracy. Ferranti Electric, Inc., 30 Rockefeller Plaza, New York, N. Y.

**Fluorescent Lamp Capacitors.**—Bulletin 4 pp. Includes data on fluorescent lamp power factor correction; standard capacitors available; tables illustrating the maximum number of lamps that may be connected with and without correction; capacitor requirements for any given number of units, etc. Aerovox Corporation, New Bedford, Mass.

**Resistance Standards.**—Bulletin 810J. Describes a new "800" series, accurately calibrated resistance standards, from 1 ohm to 10 megohms, in single units and in various combinations. They are designed for d-c and a-c measurements and provide dependable apparatus for electrical measurements in research engineering, teaching, and testing. Shallcross Mfg. Co., Collingdale, Pa.

**Asbestos Insulated Wires.**—Cat. 6106, 52 pp. Describes asbestos insulated wires and cables of many types applicable for all requirements where the use of such conductors is indicated. They consist of two general classes,—"All Asbestos" for open wiring in dry places, and "AVC" types, for conduit insulations or open wiring subject to excessive moisture, steam, etc. Many tables are included which give all essential data for specifications. American Steel & Wire Co., Rockefeller Bldg., Cleveland, O.



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**Angle Clamp and Thimble.**—Supplementing the angle clamp and dead-end thimble designs in which the clevis is parallel to the conductor, the Ohio Brass Co., Mansfield, Ohio, has brought out designs with the clevis at right angles to the conductor. These new devices were developed for users who prefer to have more flexibility in the vertical plane than in the horizontal plane. Angles from 10 to 120 degrees can be turned with the angle clamp without dead-ending

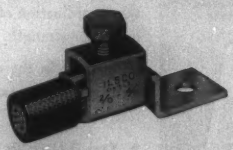
the conductors and using jumpers. No parts need be removed for attaching a conductor because it is a one-piece assembly in effect. It will accommodate any conductor from 0.162 to 0.600 inch. The dead-end thimble has an open seat which is in line with the clevis and therefore the conductor's line of pull.

**Bus Type Disconnecting Switch.**—Clamping directly on the bus bar, this new switch by the Delta-Star Electric Co., Chicago, Ill., offers a convenient oil breaker disconnect for open type switchboards. This latest design includes tongue type full floating blades, line-pressure contacts, annular ring line-pressure hinge and bolt type lock between contact and hinge to preserve head-room. Ratings are 7,500 and 15,000 volts; 400, 600, 800 and 1,200 amperes; the 400 and 600 ampere switches have single blades.

**Special Connectors.**—The connector illustrated is one of a complete line of electrical connectors and bus supports for square

tubular bus, both ventilated and unventilated types now manufactured by the Burndy Engineering Co., Inc., 459 East 133d St., New York. Clamping pressure is exerted on the corners of the tube and thereby buckling of the tube walls is prevented. Drawings are available of connectors for joining cable, round tubing, flat bar or other conductor forms to square tubing.

**Lugs and Connectors.**—The new solderless lugs and connectors by Ilsco Copper Tube & Products, Inc., 5629 Madison Rd., Cincinnati, Ohio, surpass the requirements of the Underwriters' Laboratories May 1, 1940 standard for pressure wire connectors. The bearing surfaces of their tongues are arched to fit the curves of conductors held, so that maximum contact between tongue



and conductor is assured. Short, bar-like ridges project from inner, sloping walls of a V-bottom collar, to assist in gripping wires. Smaller sizes of the new solderless lugs and connectors are equipped with fine-thread screws. Samples of the new lugs and connectors may be obtained upon request to the manufacturer.

**Carbon Black Increases Cable Life.**—The Anaconda Wire & Cable Co., New York City, has completed its development of type CB (carbon black) cable, a paper-impregnated, lead sheathed construction, and is now manufacturing it on a regular production scale. Reports from the company engineers indicate that in severe cyclic loading and aging tests simulating actual operating conditions, this new cable lasted more than twice as long as standard shielded cable and, during the test period which lasted 435 days, showed extraordinary overall stability. It is expected that the application of carbon black will be extended beyond solid-type constructions to oil-filled and gas pressure cable as well.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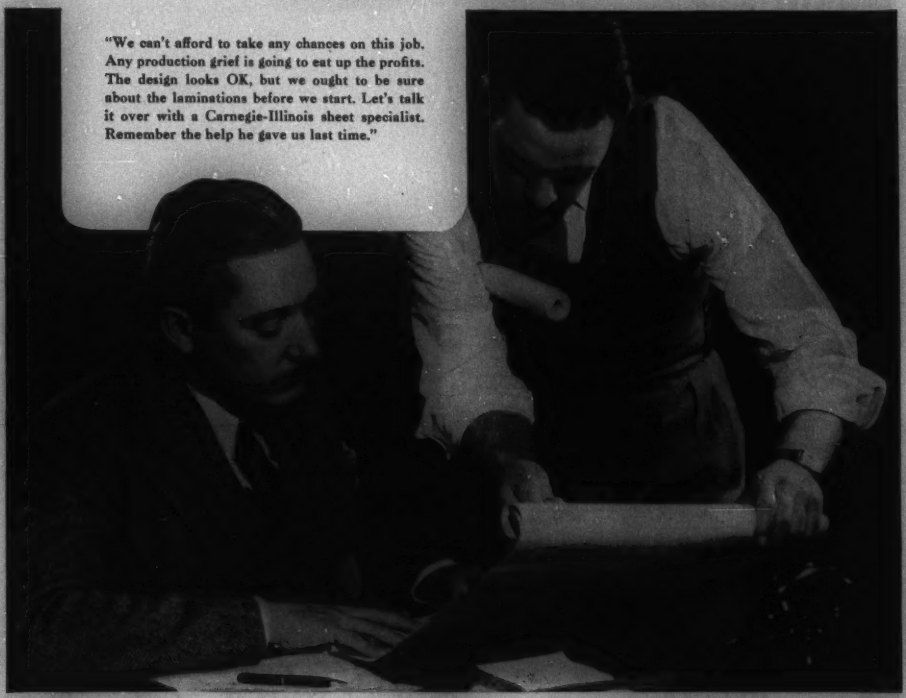
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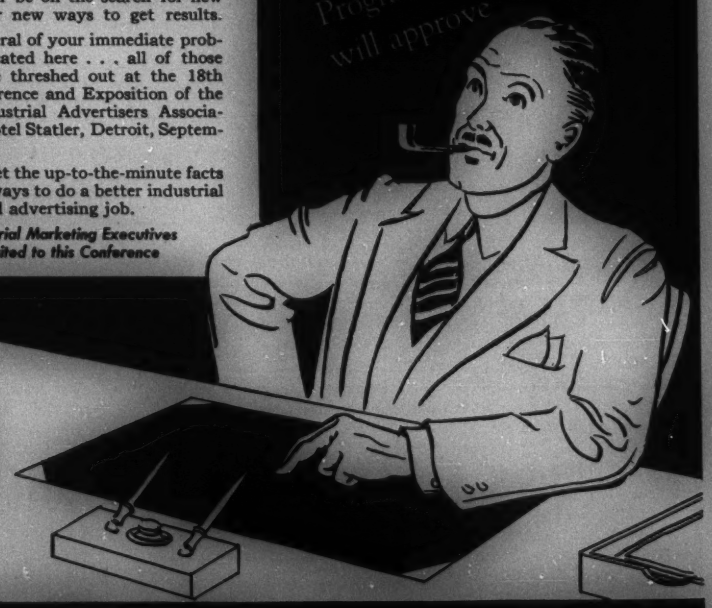

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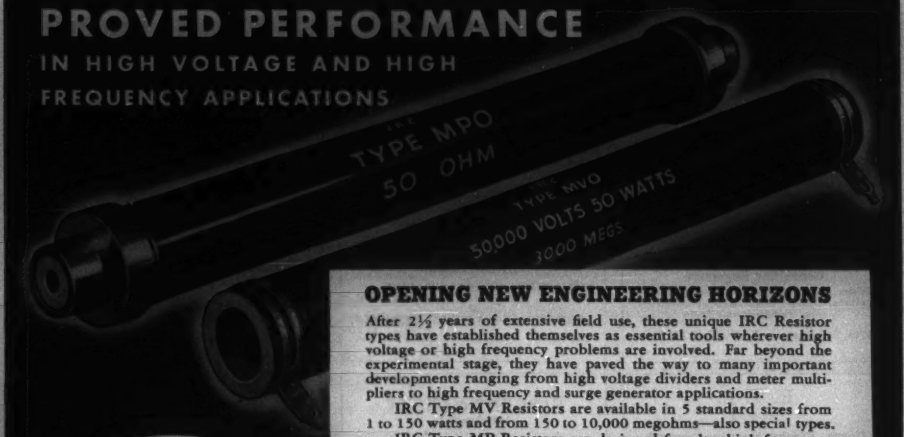


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Engineering Societies Personnel Service, Inc.

MAINTAINED for their members by the national societies of civil, mining, mechanical, and electrical engineers, in co-operation with other organizations. An inquiry to any of the four offices will bring full information. A weekly bulletin of engineering positions open is available to members of the co-operating societies at a subscription of $3 per quarter or $10 per annum, payable in advance.

**In the interest of effective service, it is essential that members using the employment service keep the bureau office serving them advised at reasonable intervals concerning their availability for employment, concerning any change in status, and immediately upon acceptance of any employment.**

Employers interested in the following announcements should address replies to the key numbers indicated, and mail to the New York office.

## Men Available

GRAD E.E., 1933; 29, single; 5 yrs exper production engg, cost, time studies, planning; practical exper machine shop, punch press work, motor change-overs, maintenance, drafting. Desires engg pos. Available immed. Location immaterial. E-676.

SERVICE ENGR; 37, single; specialized training air conditioning, refrigeration; 3 yrs installation, repair, servicing. 5 yrs mech, elec draftsman; 4 yrs teaching; full command Spanish. Accept foreign assignment. E-677.

STATISTICIAN, ELEC ENGR; 42; 18 yrs detailed knowledge foreign, domestic elec markets; originator widely used analytical methods; background RR and power plant. Editor World Elec Markets. In Who's Who in Engg, Who's Who in the East. E-678.

B.E.E., New York Univ., 1940. 1 yr engg and designing aircraft radio receivers, transmitters, associated eqpt. 6 yrs testg inspec and supervision. Desires engg pos requiring initiative and creative ability. E-679.

MANAGER OR SUPT, A.I.E.E., A.S.M.E.; 47, married; broad exper in installing, maintenance, oprn of tel and telegraph signalling and control eqpt; 9 yrs supt I/C Transoceanic Com Service. Available immed. Location immaterial. E-680.

M.S. E.E., Univ of Colorado, 1936; 35, married; 5 yrs tel, 3 yrs mfg mining machy. Util co or mfg pos desired. Prof Elec Engr, Colorado. Midwest or West preferred. E-681-407-C-1-Chicago.

E.E., 36, married; exper des of various elec and mech apparatus, motors; some lab work. Inventive ability. Knowledge handling men. Interested devpmt work with some opportunity. Newark or vicinity. E-682.

ELEC ENGR, 20 yrs exper in pwr control and application. Capable designer, estimator and maintenance engr. Exper in controls and circuits ltg, pwr plants, distr, rotating machy, instruments, com and elevators. E-683.

B.S. E.E., 1937, 27, married. Eta Kappa Nu. 3 yrs in charge of appliance dept. Desires change to draftg and des with mfr or util. Location immaterial. E-684.

ELEC ENGR, Fellow A.I.E.E., professional license, varied util, indus exper, U.S. and abroad. Past 15 yrs chief engr, gen supt, util in Mississippi Valley; exper in continuing property records. E-685.

B.S. E.E., Tufts College Engg School, 1940; 24, single; some exper in radio engg. Radio amateur. Desires pos in oprn engg in coms. Location, unimportant. Available June, 1940. E-686.

B.S. E.E.; 3 yrs Law, Night, eligible Bar many states; 28, married; 6 yrs pub util comm exper, rates, contracts, valuations, financial, depreciation and cost studies, oprtg problems, regulatory procedure. E-687.

ELEC ENGR, 18 yrs exper des, mfg, sales rotating elec machy. Chief engr several cos. Can handle engg mfg, application and sales. Seeks exec pos in elec or mech industry. E-688.

B.S. E.E., Univ. of Wisconsin, 1940. Desires pos with elec mfg co or util with future. Available immed. Salary secondary. Location, Middlewest. E-689.

E.E., R.P.I., 1928; licensed prof engr, N.Y. 8 yrs coms; 4 yrs X-ray and high voltage rectifiers. Des pos in devpmt or production. Location, New York Metropolitan Area. E-690.

B.S. E.E., 1930. Util engg, indus engg and constr, mining electrification and electrician. Interested in connection util, indus organization or mining co. Available short notice. Free to travel. E-691.

**ENGINEERING SOCIETIES PERSONNEL SERVICE, INC.**

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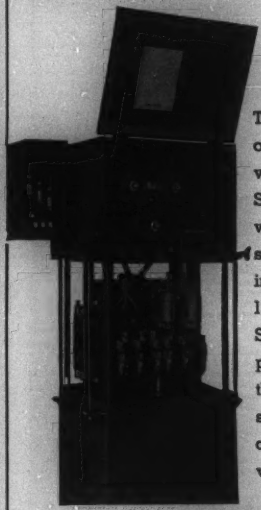

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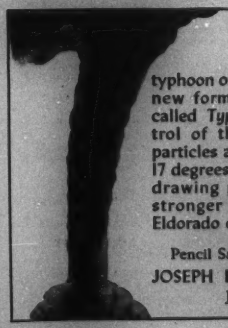

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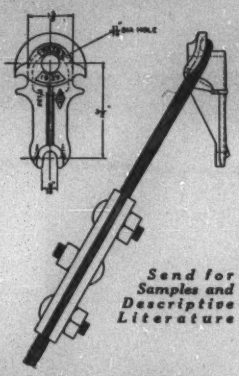

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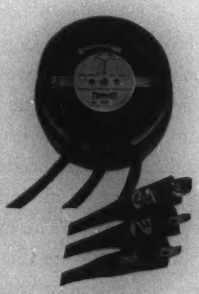

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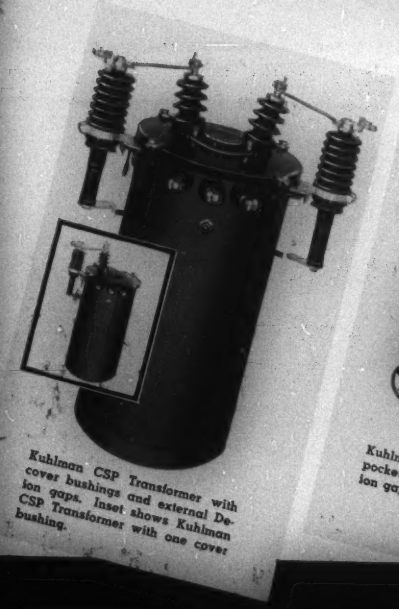
# Kuhlman C. S. P. TRANSFORMERS

## AVAILABLE IN THREE TYPES.



Kuhlman CSP Transformer with cover bushings and external De-ion gaps. Inset shows Kuhlman CSP Transformer with one cover bushing.

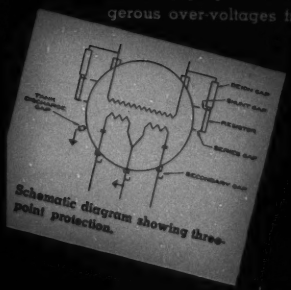
Kuhlman CSP Transformer with pocket bushings and internal De-ion gaps.

Kuhlman CSP Transformer with pocket bushings, external De-ion gaps and TR breaker with signal light.

## PROTECTS ITSELF AGAINST FAILURE DUE TO OVERLOADS AND SURGES

In the Kuhlman CSP Transformer the proven excellence of Kuhlman Distribution Transformer design is combined with accessories that result in a self-contained, completely self-protecting unit.

De-ion gaps protect the transformer against dangerous over-voltages from lightning and all other causes by equalizing stresses from the Primary winding to case and core. These gaps utilize the principle of by-passing the power of a lightning surge rather than absorbing it. They accomplish this effect by providing a path of practically zero impedance at the instant of breakdown of the protective gap.



Schematic diagram showing three-point protection.

Protection against secondary short-circuits and dangerous overloads is provided by a circuit breaker which is tripped by the combined thermal effect, on a bimetal element, of the load current and oil temperature. When the transformer is consistently operating above normal temperatures an automatic signal lamp indicates this condition.

And as a final protection, internal fusible links, co-ordinated with line fuses, prevent line outages. The sole function of this "Protective Link" is to fuse and thus disconnect the transformer from the line in the event of transformer failure from any cause. For more complete facts about the Kuhlman CSP Transformer, write for bulletin No. 340.

**KUHLMAN ☆ ELECTRIC COMPANY**

*We reprint this advertisement which first appeared in September, 1938, as an example of our early desire to promote the defense of America.*

# A NATION'S INDUSTRIES ARE ITS THIRD LINE OF DEFENSE

Armies without a constant stream of supplies are helpless in the field. Navies without material for repairs or munitions are tied to our shores. War today is a war of materials.

Modern wars are waged behind the lines, in the nation's factories. Modern war technique strives to destroy the source of munitions.

When the stream of war supplies is choked off, armies and navies are helpless. Legislation that prevents industrial expansion would affect our defense. Let us protect and encourage our industries to expand now, in time of peace, so that in a time of national emergency they will efficiently provide the sinews of war for our armed forces. The Okonite Co., Passaic, N. J., offices in principal cities.

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